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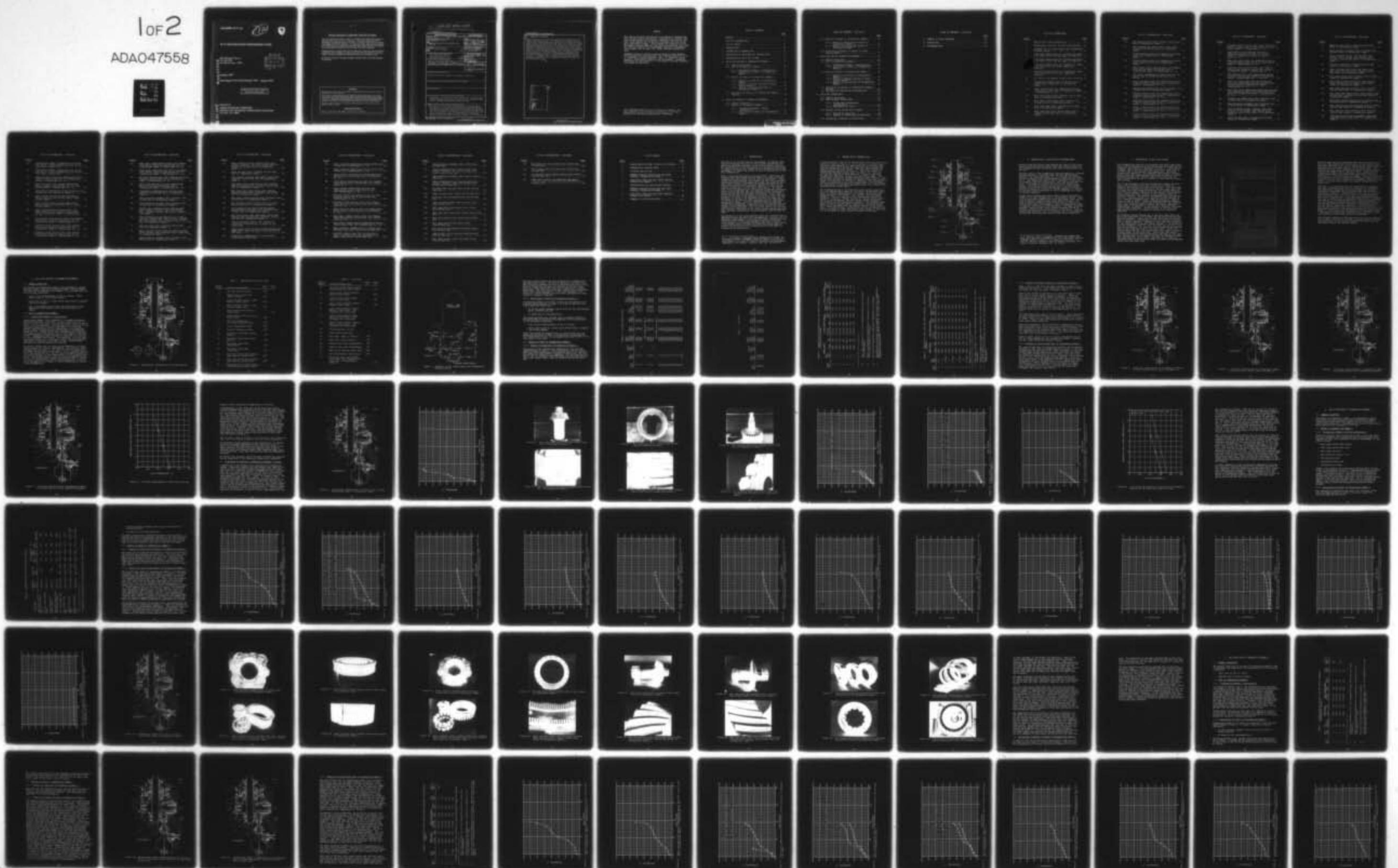

USAAMRDL-TR-77-30

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AH-1S HIGH-SURVIVABLE TRANSMISSION SYSTEM

Bell Helicopter Textron
P.O. Box 482
Fort Worth, Texas 76101

October 1977

Final Report for Period October 1975 - August 1977

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Prepared for

APPLIED TECHNOLOGY LABORATORY
RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report presents the results of tests on a modified AH-1S transmission designed to operate for 30 minutes after loss of lubrication. The design tested has shown an improvement (in operation time) of from seven to twenty-six minutes over the standard AH-1S design after loss of lubrication. The tests have further indicated that attainment of the 30-minute goal is achievable at load levels below those used during this program, but at levels which are within the flight envelope of the AH-1S helicopter.

Additional efforts are planned which will be designed to optimize the AH-1S component modifications and to establish the maximum load level that the modified AH-1S transmission can operate successfully for 30 minutes after loss of lubrication occurs.

Mr. Wayne A. Hudgins of the Systems Support Division served as the project engineer for this effort.

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The objective of the work performed on this program was to demonstrate that the AH-1S main transmission system modified with internal component improvements but without an emergency lubrication system could operate for 30 minutes following the loss of lubrication. The internal component improvements were based upon work done under a previous Eustis Directorate program conducted by Bell Helicopter Textron. Four different,

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20. ABSTRACT - continued

modified versions of the AH-1S transmission configuration were tested under this program. All loss-of-lube testing was conducted at 950 input horsepower (84 percent of maximum continuous power rating of the AH-1S) and 6600 input rpm. The first transmission configuration tested ran 7 minutes under loss-of-lube conditions before failure of the main input spiral bevel pinion occurred. The second transmission configuration ran 21 minutes before the lower planetary stage failed. The third transmission configuration ran 19 minutes before a lower planetary stage failure occurred. The fourth transmission configuration ran 26.5 minutes before, again, a lower planetary stage failure occurred. It appears that a 30-minute loss-of-lube capability has been achieved for all transmission components except the lower planetary stage.

PREFACE

This report contains the results of a program to demonstrate that the AH-1S main transmission, modified with internal component improvements but without an emergency lubrication system, could operate for 30 minutes following the loss of the main lubrication system. This program was conducted by Bell Helicopter Textron (BHT) for the Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory (USAAMRDL)* from October 1975 to April 1977 under Contract DAAJ02-76-C-0006.

USAAMRDL technical direction was provided by Wayne Hudgins. This program was conducted under the technical direction of D. J. Richardson, Project Engineer, and C. E. Braddock, Group Engineer, Transmission Research and Development. Technical assistance was provided by P. G. Williams of the BHT Transmission Research Laboratory.

*On 1 September 1977, Eustis Directorate, USAAMRDL, was redesignated Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM).

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1. INTRODUCTION

The ability of utility/tactical helicopters to complete their missions following the loss of drive system lubrication has become an important parameter in helicopter design criteria. The increased use of the helicopter as a weapons platform and in combat situations has necessitated investigation and design refinements to reduce the effect of loss of lubrication on the main transmission.

Under a previous contractual research effort, tests were conducted at Bell Helicopter Textron (BHT) on a high-survivable transmission (HST) system for the AH-1G/Q helicopter[1]. This system included component improvements as well as an emergency lubrication system. The design goal under the previous contract (Eustis Directorate Contract DAAJ02-74-C-0019) was to achieve 60 minutes of transmission operation at best cruise condition after the loss of normal lubrication. In actual test at 950 horsepower input (84 percent of maximum continuous power rating) and 6600 rpm, the high-survivable transmission system for the AH-1G/Q operated successfully for 4.0 hours following the loss of the normal lubrication. After approximately 1-1/2 hours of the emergency lubrication test run, the emergency oil supply was exhausted and thus the remaining 2-1/2 hours of the test run were completed with no lubrication system functioning. The test indicated that the improved transmission components in the form of silver-plated steel retainers for the bearings, CEVM M-50 steel rollers and roller guides in the planetaries, plus increased outer race curvature (and internal clearance) of the input triplex bearing may have been the major contributors to the extensive loss-of-lube run time.

The objective of the work performed under this contract was to demonstrate that the AH-1S main transmission, modified with the component improvements of the high-survivable transmission for the AH-1G/Q but without the emergency lubrication system, could operate for 30 minutes following the loss of lubrication. A test program which included loss-of-lubrication tests on each of two modified AH-1S transmissions was undertaken to accomplish the program goal.

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[1]D. J., Richardson, HIGH-SURVIVABLE TRANSMISSION SYSTEM, Bell Helicopter Textron; USAAMRDL Technical Report 76-8, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, May 1976, AD A025930.

2. PRESENT AH-1S TRANSMISSION

A cross-sectional view of the present Bell AH-1S type main transmission is shown in Figure 1. It is similar to the UH-1 configuration and consists of a bevel gear set at the main input from the engine which drives the main rotor mast through two epicyclic planetary gear trains. The gear ratio between the engine and main rotor is 20.383 to 1. Tail rotor power is transmitted through the main input gearshaft to a spur gear set and then through a bevel gear set, located in the main transmission sump case, to the tail rotor drive shaft. The transmission rating for maximum continuous power (MCP) is 1134 shp at 6600 rpm and its rating for takeoff, hover, and low-speed flight is 30 minutes at 1290 shp at 6600 rpm. The accessory drives incorporated on the main transmission are a dual hydraulic pump drive, a tachometer generator drive, and a heating and ventilating fan blower drive.

The transmission has a wet-sump lubrication system consisting of a 10.5-gpm pressure pump, an oil cooler, an automatic emergency oil cooler bypass system, a pressure relief valve and bypass manifold, oil filters, jets, valves, and associated hardware. The oil capacity of the transmission lubrication system is 11 quarts. Except for the oil cooler and the emergency oil cooler bypass, the lubrication system components are integral to the transmission assembly. The automatic emergency oil cooler bypass system consists of a balanced piston device which operates when low pressure exists in the cooler loop. With this system, if the cooler and its associated lines are hit or begin to leak, the bypass valve routes oil directly to the transmission upon sensing a pressure difference.

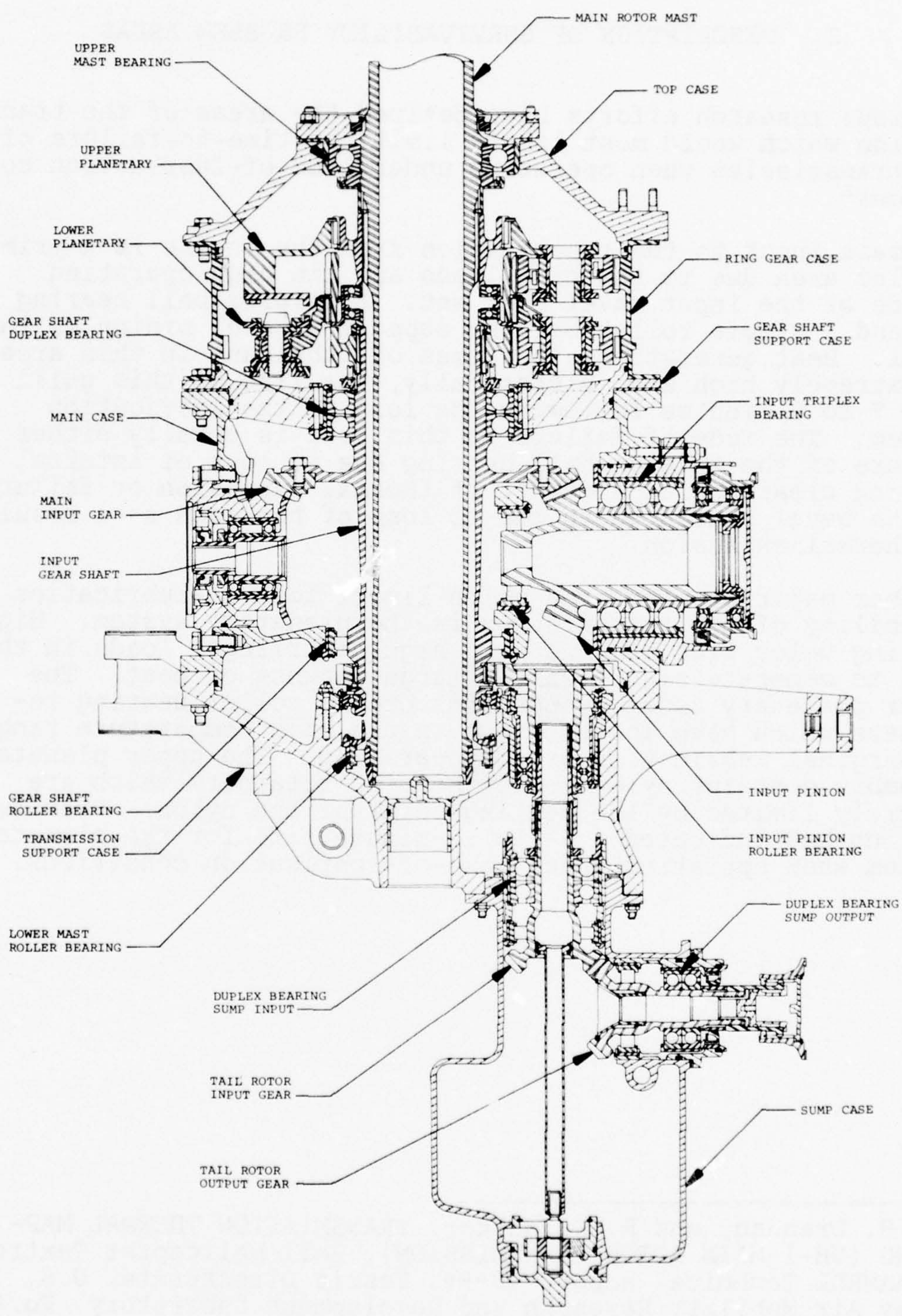

Figure 1. Typical AH-1S type transmission.

3. DESCRIPTION OF SURVIVABILITY PROBLEM AREAS

Previous research efforts have defined the areas of the transmission which would most likely limit the time-to-failure of the transmission when operating under loss-of-lubrication conditions[2].

The main input to the transmission from the engine is a primary problem area due to the high loads and the high operating speeds of the input bevel gear set. A triplex ball bearing set and a single roller bearing support a bevel pinion in this quill. Heat generation after loss of lubricant in this area is extremely high and, historically, the life of this quill is only 7 to 9 minutes following the loss of the lubrication system. The mode of failure in this area is usually either seizure of the triplex ball bearing due to loss of internal bearing clearance as a result of thermal expansion or failure of the bevel pinion teeth due to loss of backlash as a result of thermal expansion.

Another major problem area which limits loss-of-lubrication capability of the transmission is the planetary system. High sliding velocities combine with high centrifugal loads in this area to generate significantly large amounts of heat. The lower planetary assembly contains bronze roller bearing retainers which have low strength in the high temperature range of marginal lubrication or dry operation. The upper planetary assembly contains nylon roller bearing retainers which are severely limited by the melting point of the nylon. Previous testing had indicated a 6- to 12-minute life for the planetary system when operating under loss-of-lubrication conditions.

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[2] J. H. Drennan, and R. D. Walker, TRANSMISSION THERMAL MAPPING (UH-1 MAIN ROTOR TRANSMISSION), Bell Helicopter Textron; USAAMRDL Technical Report 73-90, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, December 1973, AD 777803.

4. DESCRIPTION OF AH-1S HST SYSTEM

The transmissions used for this program were UH-1D types modified to AH-1S configurations and further modified with the HST component improvements as described in Table 1. Additionally, a carbon radial seal was installed in the main input area of the AH-1S HST to accommodate high-temperature, lubricated transmission operation. The component improvements incorporated on these two transmissions were based on results of work performed by BHT under Contract DAAJ02-74-C-0019 with the Eustis Directorate as well as results of other BHT oil starvation testing.

All of the bearings in the main transmission except the bearings in the accessory drive quills and the freewheeling assembly were modified for this test program. With the exceptions of the triplex ball bearing in the main input quill and the upper and lower planetary bearings, the bearing modification in each instance consisted of installing a silver-plated steel bearing retainer in place of the standard bronze or nylatron retainer. The maximum recommended operating temperature for a machined bronze or a nylatron bearing retainer is 275°F, whereas a machined steel cage can operate at temperatures as high as 800°F. These recommended operating temperatures are for properly lubricated conditions but the machined steel cage, being stronger at normal and higher operating temperatures, is superior to the bronze or nylatron cage under loss-of-lube conditions. Silver plating of the steel cage adds lubricity which is beneficial during oil starvation operation.

The standard triplex bearing set in the main input quill has balls and races made of M-50 steel and has silver-plated steel bearing retainers. Under loss-of-lube conditions the typical mode of failure of this bearing is loss of internal clearance due to thermal expansion. Therefore, the outer race curvature of this bearing was increased from 52 percent to 54 percent of the ball diameter, which not only increased the internal clearance of the bearing .003 inch but also transferred the bearing race control from the outer to the inner race. Inner race control means that ball rolling occurs at the inner race while sliding occurs at the outer race. With inner race control, this modified triplex bearing generates less heat at the inner race and more heat at the outer race than the standard triplex. This modification, then, tends to prevent loss of bearing clearance which occurs when the inner race heats up and expands faster than the outer race.

TABLE 1. BEARING MODIFICATIONS FOR AH-1S HST TESTING

PART NUMBER	DESCRIPTION	STANDARD AH-1S CONFIGURATION	TRANSMISSION NO. 1, RETEST OF TRANSMISSION AND TRANSMISSION NO. 2 CONFIGURATION (SAME AS STD EXCEPT AS NOTED)	FOURTH TEST CONFIGURATION
205-040-246-3	MAIN INPUT TRIPLEX BRG	M-50 BALLS & RACES, SPS CAGE, OUTER RACE CURVE = 52%	OUTER RACE CURVE = 54% & INCREASED CLEARANCE	SAME AS TRANSMISSION 1 & 2
205-040-249-1	INPUT PINION ROLLER BRG	M-50 ROLLERS & RACES, BRONZE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
205-040-245-1	INPUT GEARSHAFT DUPLEX BRG	M-50 BALLS & RACES, NYLATRON CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
204-040-725-1	LOWER PLANETARY ROLLER SET	52100 STL	M-50 STL	SAME AS TRANSMISSION 1 & 2
204-040-133-1	LOWER PLANETARY BRG CAGE	BRONZE	SPS	SAME AS TRANSMISSION 1 & 2
204-040-132-1	LOWER PLANETARY BRG INNER RACE	52100 STL	STD	M-50 STL, .0005 INCH UNDERSIZE O.D.
204-040-134-5	LOWER PLANETARY ROLLER GUIDE	AMS 6260 STL	M-50 STL	SAME AS TRANSMISSION 1 & 2
204-040-135-1	LOWER PLANETARY SUPPORT BRG	52100 BALLS & RACES, BAKELITE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
204-040-725-1	UPPER PLANETARY ROLLER SET	52100 STL	M-50 STL	SAME AS TRANSMISSION 1 & 2
204-040-129-1	UPPER PLANETARY BRG CAGE	NYLON	SPS	SAME AS TRANSMISSION 1 & 2
204-040-134-5	UPPER PLANETARY ROLLER GUIDE	AMS 6260 STL	M-50 STL	SAME AS TRANSMISSION 1 & 2
204-040-135-1	UPPER PLANETARY SUPPORT BRG	52100 BALLS & RACES, BAKELITE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
204-040-271-3	LOWER GEARSHAFT ROLLER BRG	52100 ROLLERS & RACES, BRONZE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
204-040-270-3	LOWER MAST ROLLER BRG	52100 ROLLERS & RACES, BRONZE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
204-040-135-1	T/R TAKE-OFF BALL BRG	52100 BALLS & RACES, BAKELITE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
212-040-210-1	T/R TAKE-OFF ROLLER BRG	52CB ROLLERS & RACES, BRONZE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
204-040-424-1	T/R TAKE-OFF DUPLEX BRG	52100 BALLS & RACES, NYLATRON CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
212-040-210-1	T/R DR, SUMP INPUT ROLLER BRG	52CB ROLLERS & RACES, BRONZE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
212-040-144-1	T/R DR, SUMP INPUT DUPLEX BRG	52100 BALLS & RACES, NYLATRON CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
212-040-210-1	T/R DR, SUMP OUTPUT ROLLER BRG	52CB ROLLERS & RACES, BRONZE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
212-040-143-1	T/R DR, SUMP OUTPUT DUPLEX BRG	52100 BALLS & RACES, NYLATRON CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2
204-040-136-9	UPPER MAST BALL BRG	M-50 BALLS & RACES, BRONZE CAGE	SPS CAGE	SAME AS TRANSMISSION 1 & 2

SPS - SILVER-PLATED STEEL

Both the upper and lower planetary bearings were modified by replacing the standard AISI 52100 steel rollers with rollers made from CVEM M-50 steel and by replacing the standard bearing retainers with retainers made of silver-plated steel. The standard AMS 6260 steel planetary roller guides were replaced with roller guides made of CEVM M-50 steel. These material changes were made to allow operation of the planetaries to continue even under the severe high temperature conditions which exist in a loss-of-lube environment. With its inherently high hardness and high compressive strength at temperatures up to 800°F, as well as its long-time hot-hardness properties and temper resistance, M-50 steel is a logical choice for this application.

Although it was suspected that the standard AH-1S planetary gear mesh clearances might not be sufficient to accommodate the temperature gradients which occur under loss-of-lube conditions, these gear mesh clearances were not increased for transmission number 1. Increasing the AH-1S planetary gear mesh clearances would require 12 new or reworked planetary pinions per transmission. Since the modifications dictated by this test program may be incorporated into the AH-1S transmission design, it was determined that it would be worthwhile to test the standard planetary gear mesh clearances because of the savings which would be realized if the planetary pinions did not require additional clearances. Twelve planetary pinions were reworked under this contract to provide additional gear mesh clearances in the planetary stages of transmission number 2 in the event that the testing of transmission number 1 indicated that additional clearances were required to meet the 30-minute loss-of-lube operation requirement.

The standard elastomeric type main input oil seal was replaced with a radial carbon seal in order to provide better sealing characteristics at the elevated temperatures which would be encountered during the thermal testing.

5. AH-1S HST TESTING OF TRANSMISSION NUMBER 1

5.1 GENERAL OBJECTIVES

The testing of transmission number 1 was performed to verify previous thermal data points generated under Contract DAAJ02-74-C-0019 and to determine the response of the transmission to the following conditions:

- Loss of full effectiveness of the oil cooler. (This could be due to loss of the blower.)
- Total loss of the oil cooler which would result in operating on full bypass.
- Loss of the bypass valve and/or the lower part of the sump which would result in the loss of the main oil supply.

5.2 TEST OF TRANSMISSION NUMBER 1

5.2.1 Transmission Number 1 Configuration

Transmission number 1 was assembled to a standard production AH-1S configuration except that a carbon radial seal was installed in the main input quill and the modifications listed in Table 1 were incorporated. Thermocouples were installed in the locations indicated in Figure 2 and Table 2 to allow the thermal characteristics of the transmission to be monitored during testing. Temperatures were recorded on two Honeywell Electronic 16, 24-point strip chart recorders which were type K (alumel-chromel) calibration with a full range of -200°F to 1000°F. Temperatures were recorded at intervals of 2 minutes or less throughout the testing. Oil pressure, oil flow, main rotor mast torque, tail rotor mast torque, and input rpm were recorded at intervals of 6 minutes or less. MIL-L-23699B lubricant was used throughout the testing.

A system to enable the oil cooler to be bypassed or to simulate a severed oil line was implemented. The system is shown schematically in Figure 3. Oil from the main oil sump could be pumped through any of three paths: (1) by closing valves A and C and opening valve B, the oil could be pumped through the oil cooler and back to the transmission; (2) by closing valves B and C and opening valve A, the oil could be pumped directly back to the transmission without going through the oil cooler; or (3) by closing valves A and B and opening valve C, the oil could be pumped into a remote oil tank, preventing its return to the transmission.

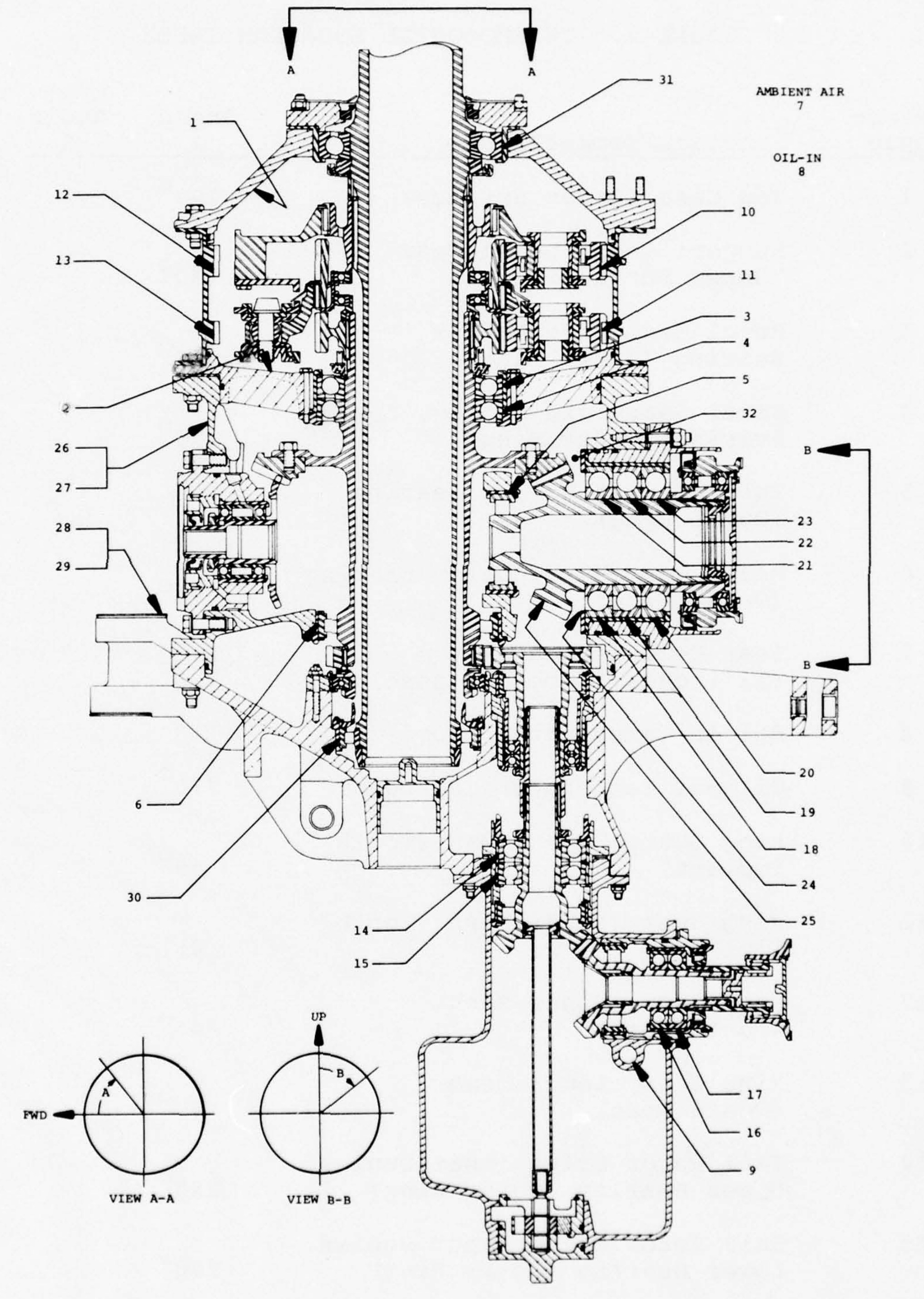

Figure 2. Thermocouple locations for AH-1S HST testing.

TABLE 2. THERMOCOUPLE LOCATION INDEX

Thermo-couple	Location/Nomenclature	Angle A	Angle B
1	Top Case (Inner Surface)	190°	
2	Support Case, Bevel Gear (Upper Surface)	190°	
3	Bevel Gearshaft Duplex, Upper Bearing (Outer Ring)	270°	
4	Bevel Gearshaft Duplex, Lower Bearing (Outer Ring)	270°	
5	Input Pinion Roller Bearing (Outer Ring)		30°
6	Bevel Gearshaft Roller Bearing (Outer Ring)	120°	
7	Test Cell Ambient Air (12 inches from main case)	270°	
8	Oil-in Temperature Probe	120°	
9	Oil-out Temperature Probe	270°	
10	Ring Gear, Upper Mesh (Tooth Implant)	45°	
11	Ring Gear, Lower Mesh (Tooth Implant)	45°	
12	Ring Gear, Upper Mesh (Tooth Root)	40°	
13	Ring Gear, Lower Mesh (Tooth Root)	40°	
14	Tail Rotor Drive Input Duplex, Upper Bearing (Outer Ring)	280°	
15	Tail Rotor Drive Input Duplex, Lower Bearing (Outer Ring)	280°	
16	Tail Rotor Drive Output Duplex, Inboard Bearing (Outer Ring)		50°

TABLE 2. Continued

Thermo-couple	Location/Nomenclature	Angle A	Angle B
17	Tail Rotor Drive Output Duplex, Outboard Bearing (Outer Ring)		50°
18	Input Pinion Inboard Triplex Bearing (Outer Ring)		250°
19	Input Pinion Center Triplex Bearing (Outer Ring)		80°
20	Input Pinion Outboard Triplex Bearing (Outer Ring)		85°
21	Input Pinion Inboard Triplex Bearing (Inner Ring) - Not installed for Fourth Test		
22	Input Pinion Center Triplex Bearing (Inner Ring) - Not installed for Fourth Test		
23	Input Pinion Outboard Triplex Bearing (Inner Ring) - Not installed for Fourth Test		
24	Triplex Bearing, Oil-Out		
25	Input Pinion Tooth Root		
26	Main Case, Upper 1/3 Section	95°	
27	Main Case, Center Section	85°	
28	Support Case, Main Transmission	85°	
29	Support Case, Main Transmission	95°	
30	Mast Roller Bearing (Outer Ring)	300°	
31	Mast Ball Bearing (Outer Ring)	120°	
32	Bevel Gear Mesh (Out-of-Mesh Airstream) - Not Installed for First Test of Transmission Number 1.		20°

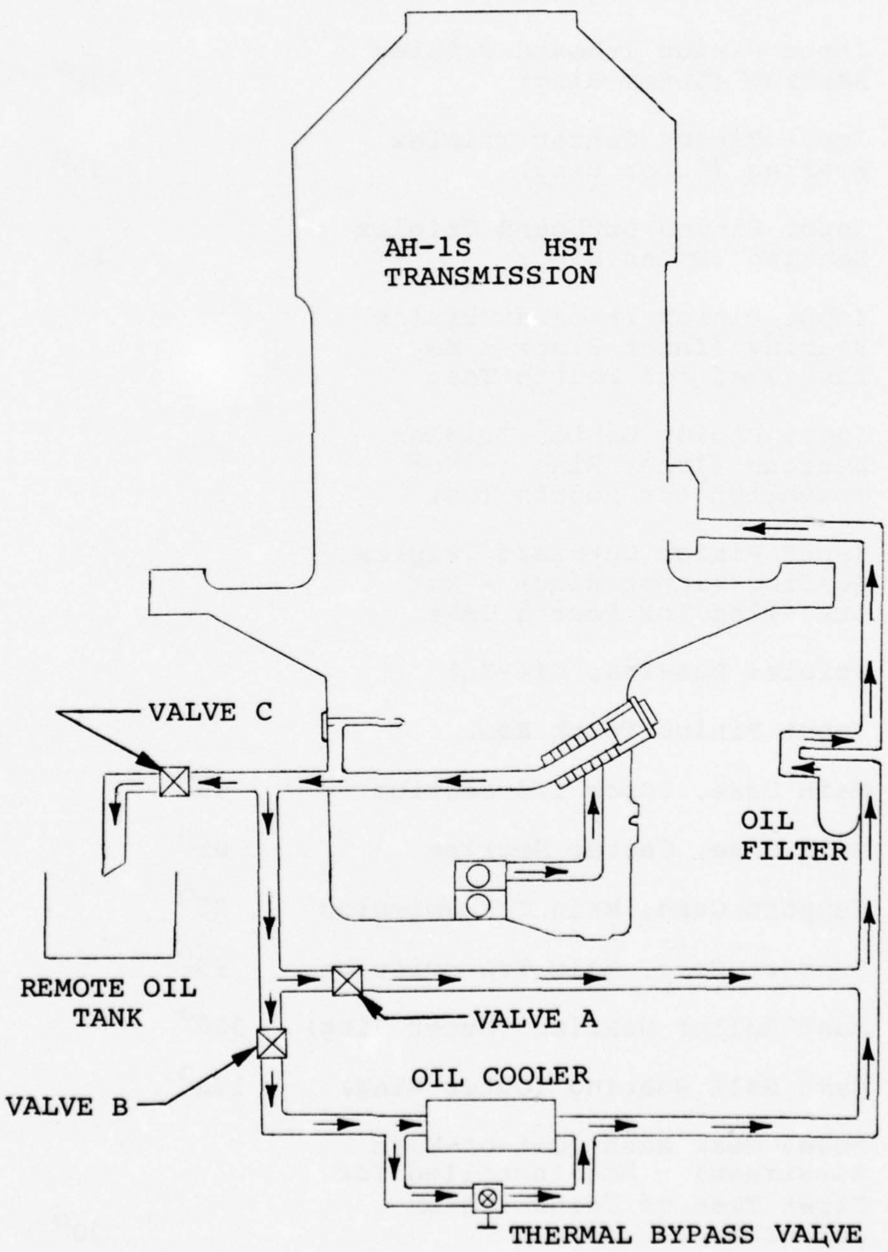

Figure 3. Schematic of oil cooler bypass and transmission drainage system.

The test stand utilized for this program was a regenerative/absorption-type stand. Torque was applied to the main rotor mast through a regenerative loop by rotating the "slave transmission" planetary ring gear in relation to the main case. Main rotor mast torque was monitored by employing a strain-gaged mast. The tail rotor loop was loaded using a 300-horsepower water brake dynamometer. Power was supplied to the system by a 500-horsepower electric motor and speed was regulated by a magnetic coupling.

5.2.2 Description of Tests of Transmission Number 1

Transmission number 1 was given a green run according to the load and speed schedule of Table 3 in order to meet the following specified objectives:

- To verify proper assembly and to give all new and modified parts a break-in period.
- To check out all instrumentation.

Following the green run, thermal tests according to Table 4 were performed to determine the response of the transmission to the following conditions:

- Loss of full effectiveness of the oil cooler.
- Total loss of the oil cooler which would result in operating on full bypass.

After concluding the thermal tests, a loss-of-lube test was conducted according to Table 5 to determine the response of the transmission to loss of the bypass valve and/or loss of the lower part of the sump.

5.3 RESULTS OF TESTS OF TRANSMISSION NUMBER 1

5.3.1 Results of Green Run of Transmission Number 1

The green run was successfully completed per the load and speed schedule of Table 3. The transmission and the instrumentation functioned properly during the green run. The post-run inspection indicated all components were functioning normally. An oil leakage of approximately 1 ml per hour past the main input carbon radial seal was observed during the green run.

TABLE 3. 2.8-HOUR RUN-IN CYCLE

Step No.	Run Time (hr)	Accum Run Time (hr)	Main Xmsn Input Speed (rpm)	Input Power (hp)	Mast Speed (rpm)	Mast Torque (in.-lb)	Tail rotor output speed (rpm)	Tail rotor output torque (in.-lb)
1	.1		4000	min	196	min	2608	min
2	.1		4450	88	218	25,534	2901	350
3	.1		4900	97	241	25,534	3194	350
4	.1	.5	5350	106	263	25,534	3488	350
SHUT DOWN TEST STAND								
6	.2		5800	284	285	63,084	3781	600
7	.2		6200	470	304	87,116	4042	700
8	.2		6600	571	324	111,148	4303	800
9	.2	1.3	7040	740	346	135,180	4590	900
SHUT DOWN TEST STAND								
10	.1		5800	897	285	198,362	3781	1250
11	.1		6000	929	295	198,475	3911	1498
12	.1		6200	961	304	199,233	4042	1793
13	.1		6400	1065	314	213,763	4172	2039
14	.1		6400	1065	314	213,763	4172	1510
15	.1		6400	1065	314	213,763	4172	2341
16	.1		6400	1092	314	219,218	4172	1133
17	.1		6400	1062	314	213,160	4172	2643
18	.1		6400	1062	314	213,160	4172	1133
19	.1		6400	1030	314	206,738	4172	3021
20	.1		6600	1175	324	228,562	4303	1098
21	.1		6600	1030	324	200,357	4303	3222
22	.1		6600	1175	324	228,562	4303	1098
23	2 min		6600	1000	324	194,521	4303	3515

TABLE 3. Continued

Step No.	Run Time (hr)	Accum Run Time (hr)	Main Xmsn Input Speed (rpm)	Input Power (hp)	Mast Speed (rpm)	Mast Torque (in.-lb)	Tail rotor output speed (rpm)	Tail rotor output torque (in.-lb)
24	3 min		6600	1000	324	194,521	4303	1098
25	2 min		6600	1000	324	194,521	4303	3515
26	3 min		6600	1000	324	194,521	4303	1098
27	2 min		6600	1000	324	194,521	4303	3515

TABLE 4. THERMAL BASELINE TESTING LOAD AND SPEED SCHEDULE, TRANSMISSION NUMBER 1

		XMSN INPUT		MAIN ROTOR MAST			TAIL ROTOR MAST			
Step No.	Run Time (hr)	(rpm)	a (hp)	Torque (in.-lb)	(hp)	Lift Load (lb)	Shear Load (lb)	Torque (in.-lb)	(hp)	Oil-In Temp b (°F)
1	c	6600	950	176,042	905	7200	575	1143	30	200
2	c	6600	950	176,042	905	7200	575	1143	30	250
3	c	6600	950	176,042	905	7200	575	1143	30	300
4	c	6600	950	176,042	905	7200	575	1143	30	350
5	c	6600	1134	176,042	1056	7200	575	2286	60	350
6	0.3	6600	950	176,042	905	7200	575	1143	30	230
7	d	6600	950	176,042	905	7200	575	1143	30	---

a. This value includes 1.6% of the transmitted main rotor and tail rotor horsepower.

b. These are stabilized temperatures; stabilized is defined as 1°F or less change in 0.1 hour.

c. Run until the specified stabilized temperature is attained.

d. Run with the oil cooler on full bypass until the oil-in temperature stabilizes or until the temperature of the hottest monitored component reaches 400°F.

TABLE 5. LOSS-OF-OIL TEST LOAD AND SPEED SCHEDULE, TRANSMISSION NUMBER 1

		XMSN INPUT		MAIN ROTOR MAST			TAIL ROTOR MAST			
Step No.	Run Time (hr)	(rpm)	a (hp)	Torque (in.-lb)	(hp)	Lift Load (lb)	Shear Load (lb)	Torque (in.-lb)	(hp)	Oil-In Temp b (°F)
1	0.3	6600	950	176,042	905	7200	575	1143	30	230
2 c	.8	6600	950	176,042	905	7200	575	1143	30	---
3	30 Sec	6600	1032	176,042	905	7200	575	4192	110	---
4	.1	6600	950	176,042	905	7200	575	1143	30	---
5	30 Sec	6600	1032	176,042	905	7200	575	4192	110	---
6	.1	6600	950	176,042	905	7200	575	1143	30	---
7	30 Sec	6600	1032	176,042	905	7200	575	4192	110	---
8	.2	6600	950	176,042	905	7200	575	1143	30	---
9	30 Sec	6600	1032	176,042	905	7200	575	4192	110	---

-- REPEAT STEPS 8 & 9 UNTIL FAILURE OCCURS --

a. This value includes 1.6% of the transmitted main rotor and tail rotor horsepower.

b. These are stabilized temperatures; stabilized is defined as 1°F or less change in .1 hour.

c. Prior to initiating this step the oil shall be drained from the transmission.

5.3.2 Results of Thermal Testing of Transmission Number 1

Steps 1 and 2 of the load and speed schedule of Table 4 were completed successfully. The stabilized temperatures recorded for these two runs are shown in Figures 4 and 5.

Significant lengths of external oil lines were used to implement the oil cooler bypass system of Figure 3. These oil lines acted as oil coolers during the thermal running and prevented attainment of the 300°F stabilized oil temperature. Using this system with the oil cooler on full bypass and the transmission operating at 950 hp per step 3 of Table 4, the maximum oil temperature reached was 257°F. For this reason steps 3, 4, and 5 had to be aborted. It was decided to completely bypass the oil cooler by running one short oil line directly from the oil outlet of the transmission to the oil inlet.

This simulated total loss of the oil cooler. The transmission was then operated according to the loads and speeds of step 7 of Table 4 until the oil temperature stabilized, which occurred at 310°F. Figure 6 shows the stabilized transmission temperatures under these conditions.

With the transmission still operating on complete oil cooler bypass with the short, direct oil line, the transmission loads were increased to the levels dictated by step 5 of Table 4. The transmission was operated under these conditions until the oil temperature stabilized at 323°F. The stabilized temperatures for this run are shown in Figure 7.

Figure 8 shows a plot of the oil cooler requirements versus the oil inlet temperature for transmission number 1 based on the data taken during the thermal running.

5.3.3 Results of Loss-of-Lube Test of Transmission Number 1

The loss-of-lube test of transmission number 1 was performed according to the load and speed schedule of Table 5. The test transmission was operated at 950 input horsepower (84 percent of MCP) under normal lubrication conditions until the inlet oil temperature stabilized at 230°F. Then, with the transmission still operating at 950 input horsepower (30 hp through the tail rotor, lift and bending loads applied to the main rotor mast) valve C was opened and valves A and B were closed (reference Figure 3) forcing the oil to be pumped from the transmission. After complete loss of the main oil supply, this transmission ran for only 7 minutes before the input bevel gear mesh ran out of clearance and the teeth were stripped from the main input pinion.

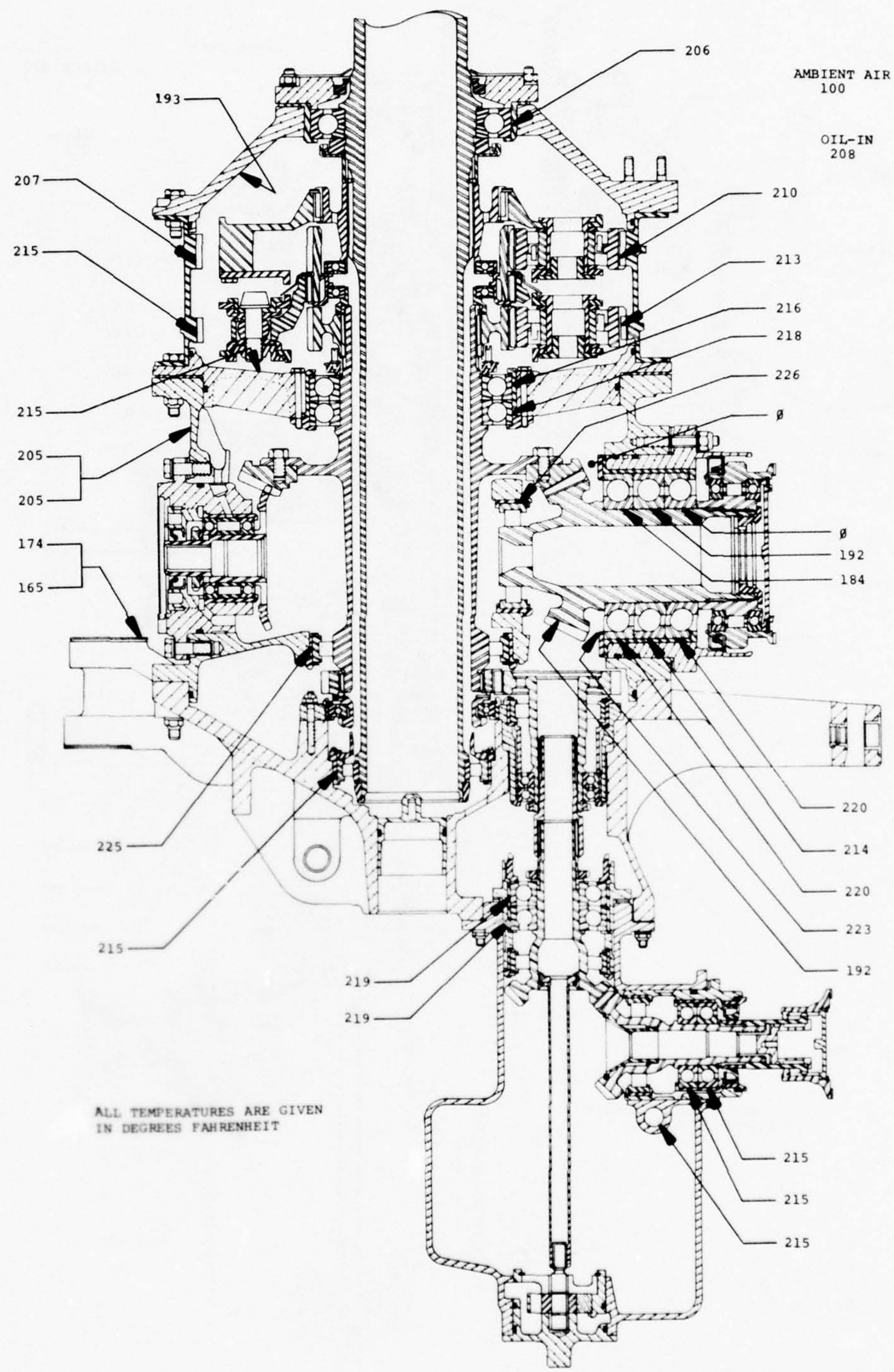

Figure 4. Stabilized temperatures for transmission number 1 at 208°F oil-in, 950 hp (step 1 of Table 4).

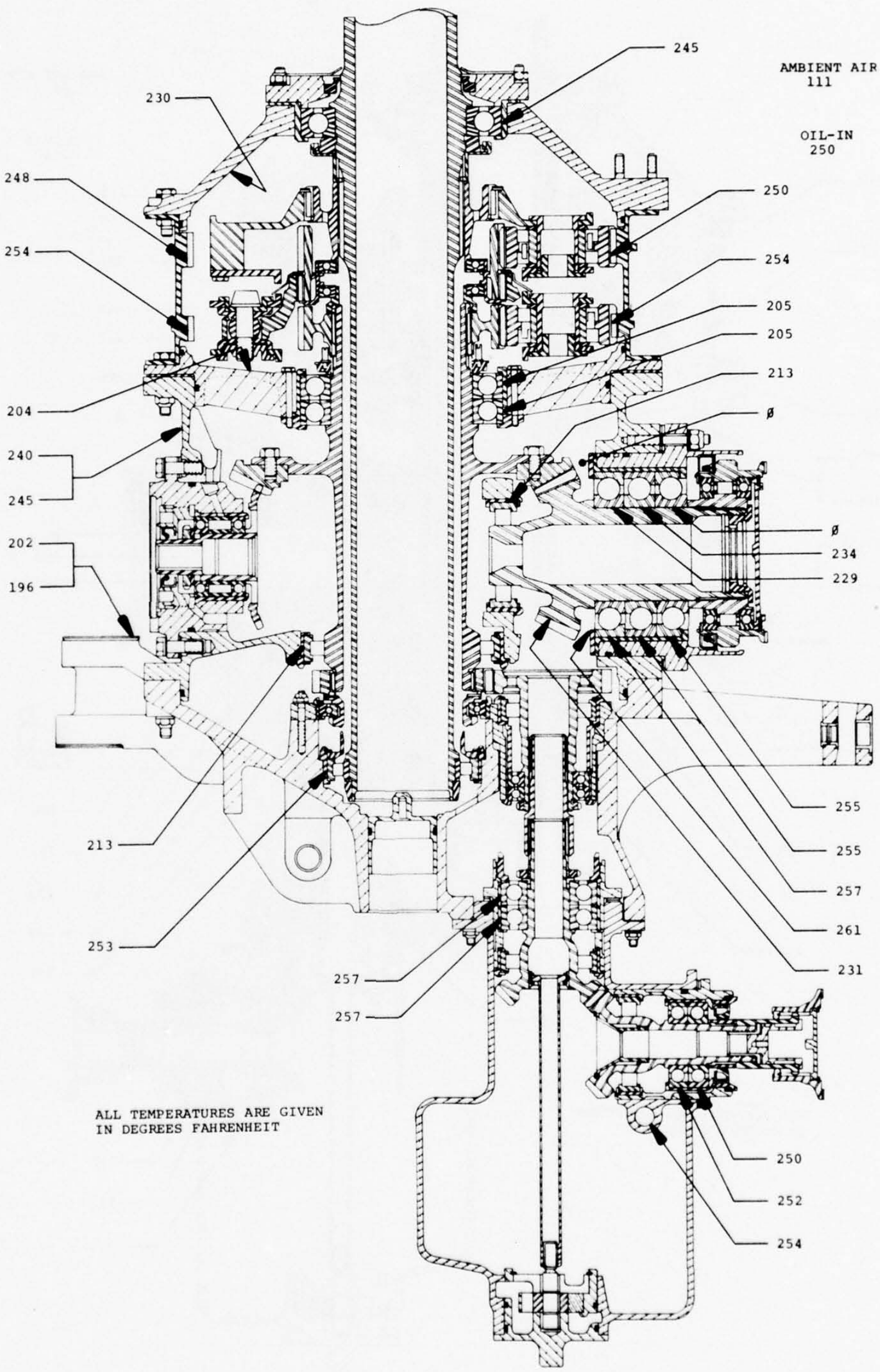

Figure 5. Stabilized temperatures for transmission number 1 at 250°F oil-in, 950 hp (step 2 of Table 4).

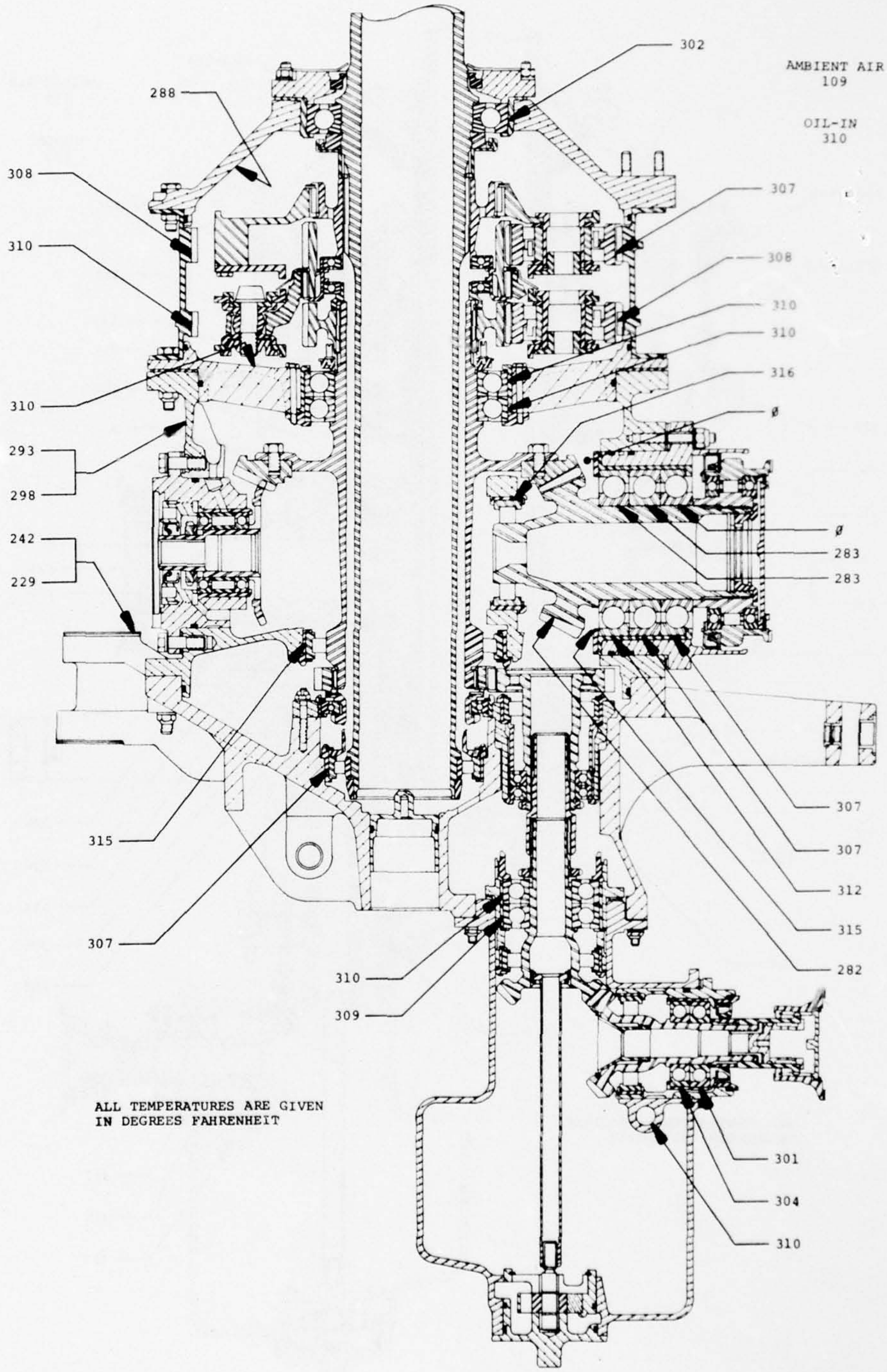

Figure 6. Stabilized temperatures for transmission number 1 at 950 hp with oil cooler completely bypassed.

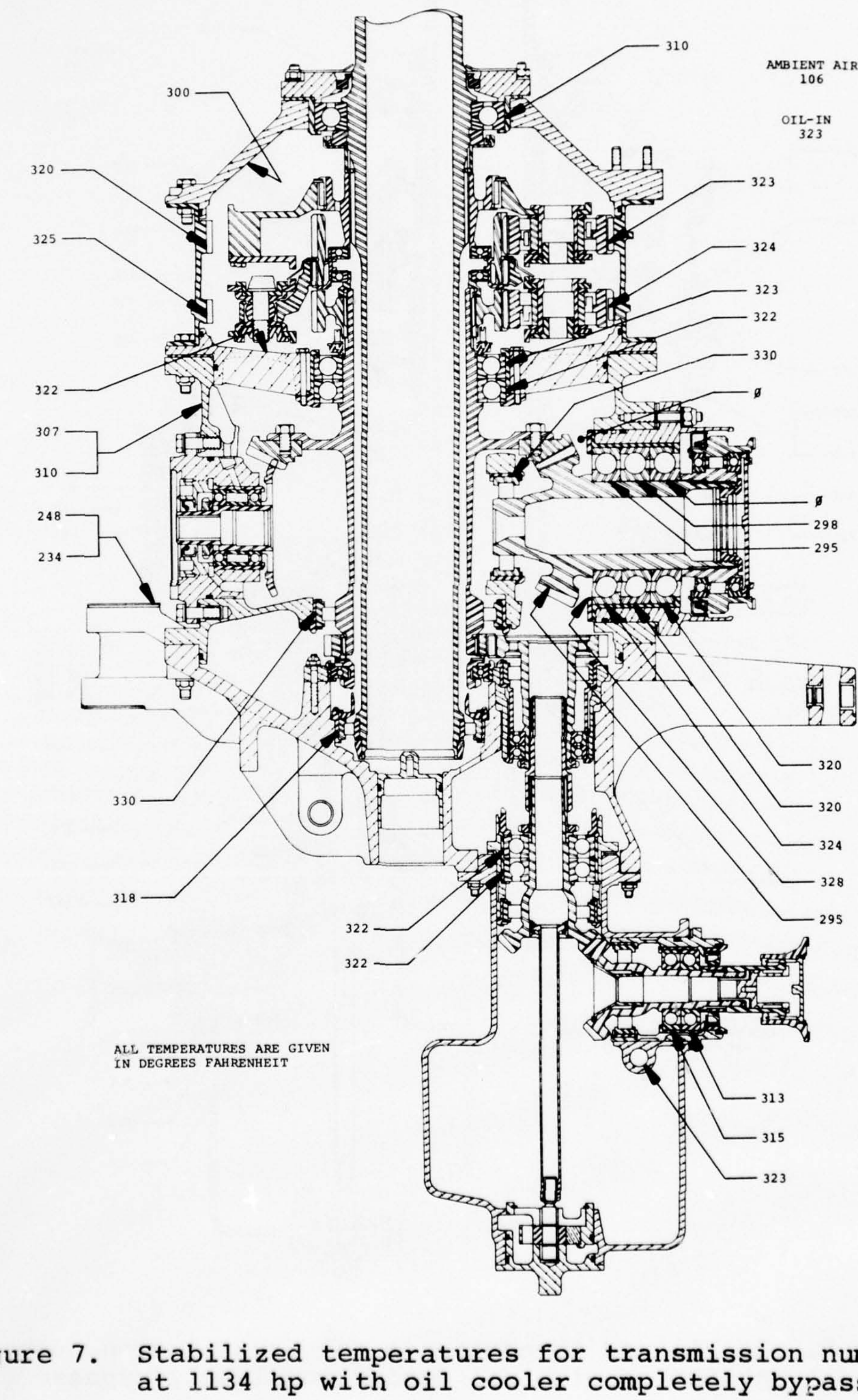

Figure 7. Stabilized temperatures for transmission number 1 at 1134 hp with oil cooler completely bypassed.

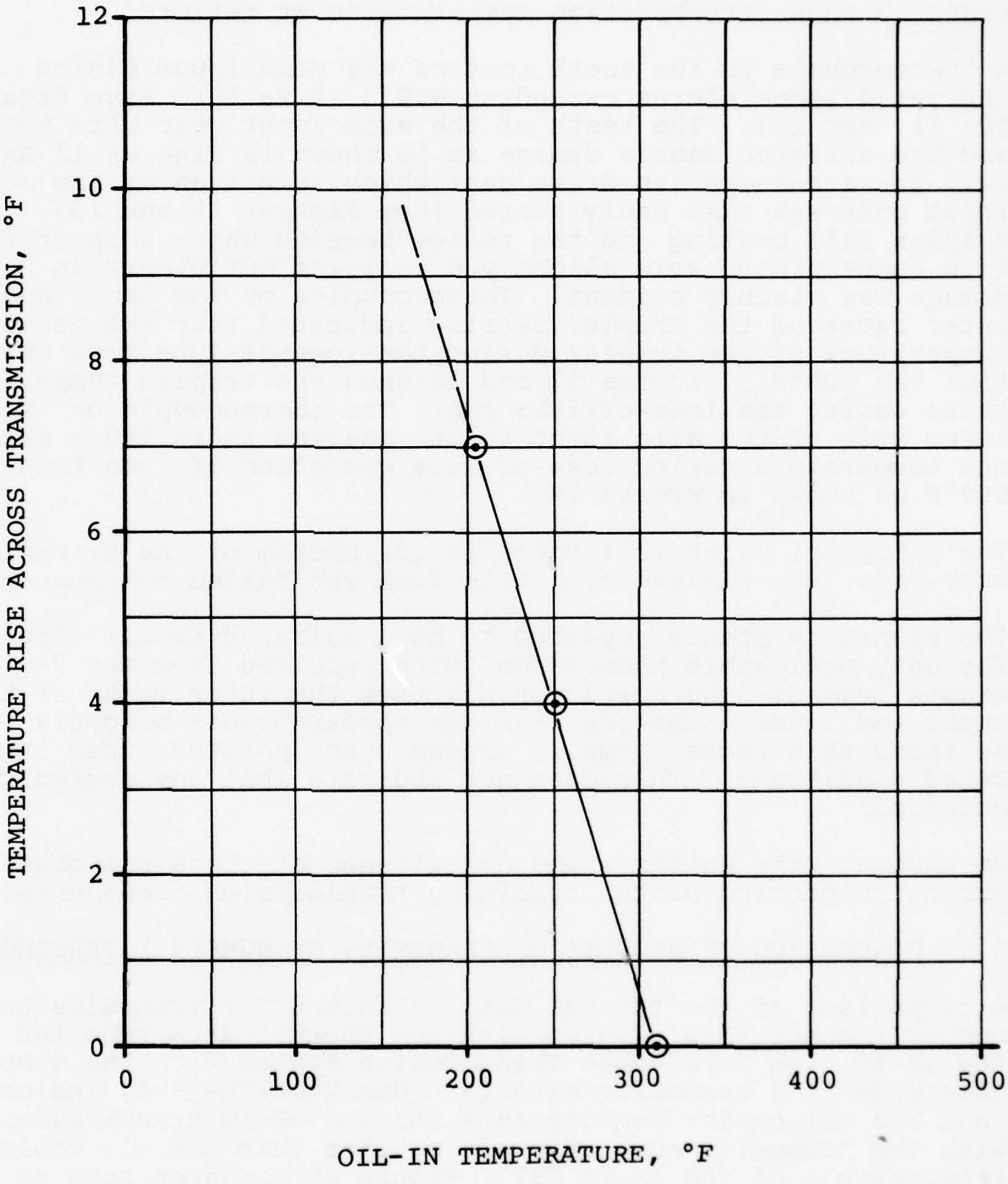

Figure 8. Oil cooler requirements of AH-1S HST at 950 hp.

Figure 9 shows transmission temperatures at failure.

A thermocouple in the tooth root of the main input pinion indicated temperatures exceeding 900°F at failure (see Figures 10, 11, and 12). The teeth of the main input gear were scored and had suffered debris damage as is shown in Figures 13 and 14. The accessory fan drive gear which is driven by the main input gear was also badly scored (see Figures 15 and 16). The triplex ball bearing and the roller bearing which support the main input pinion were slightly discolored but otherwise no damage was visibly evident. Thermocouples on the inner and outer races of the triplex bearing indicated that the maximum temperature of the triplex during the loss-of-lube test operation was 500°F. Figures 17 and 18 show the triplex temperatures during the loss-of-lube run. The thermocouple on the outer race of the main input roller bearing indicated a maximum temperature during loss-of-lube operation of less than 500°F as shown in Figure 19.

The oil pump, which is located in the bottom of the transmission sump case, was damaged by debris from the failed components.

The planetary stages appeared to have suffered no ill effects. The only noticeable phenomenon which resulted from the 7-minute loss-of-lube operation was that the outer races of the upper and lower planetary bearings appeared more brightly polished than races normally appear when operated under lubricated conditions. This does not indicate that any degradation occurred.

No unusual wear patterns and no evidence of abuse was observed during inspection of the remaining transmission components.

5.4 DISCUSSION OF RESULTS OF TRANSMISSION NUMBER 1 TESTING

A comparison of the thermal data collected for transmission number 1 under this program with the thermal data reported for the AH-1G High Survivable Transmission System with the sump case made of a composite material (USAAMRDL-TR-76-8) indicates that the oil cooler requirements for the AH-1G transmission with the composite sump case are greater than the oil cooler requirements of the AH-1S HST. Figure 20 compares some of the data generated under the two programs. In terms of heat transfer characteristics, the major difference between the AH-1G HST and the AH-1S HST is that the AH-1G HST utilizes the standard sump case made of magnesium alloy. The thermal conductivity for the E-glass epoxy composite sump materials is less than .3 BTU/hr-ft-°F which can be compared to a thermal conductivity of 41 BTU/hr-ft-°F for magnesium alloy. This probably explains the difference in the oil cooler requirements for the

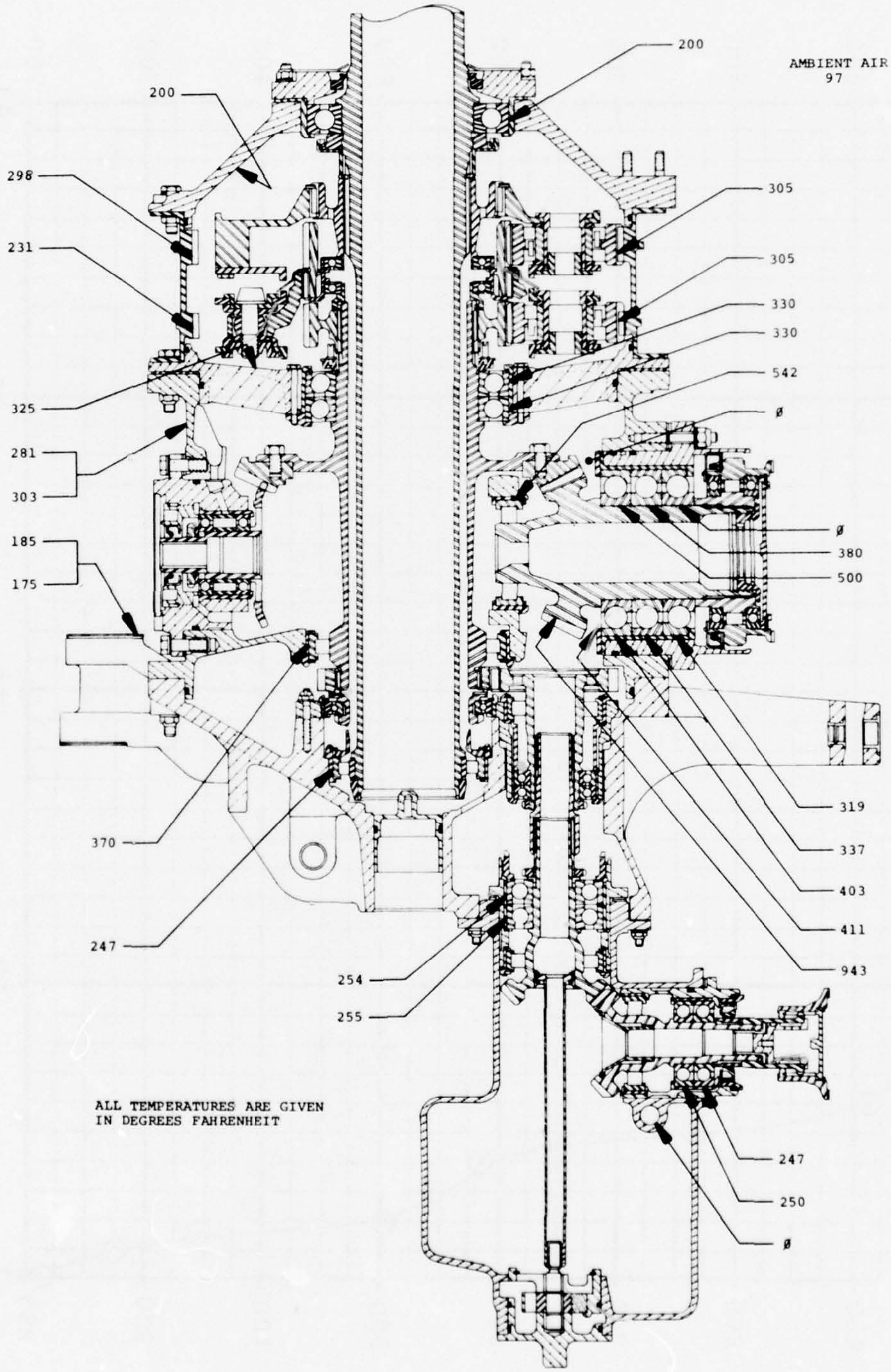

Figure 9. Transmission temperatures at failure after 7-minute loss-of-lube test of transmission number 1.

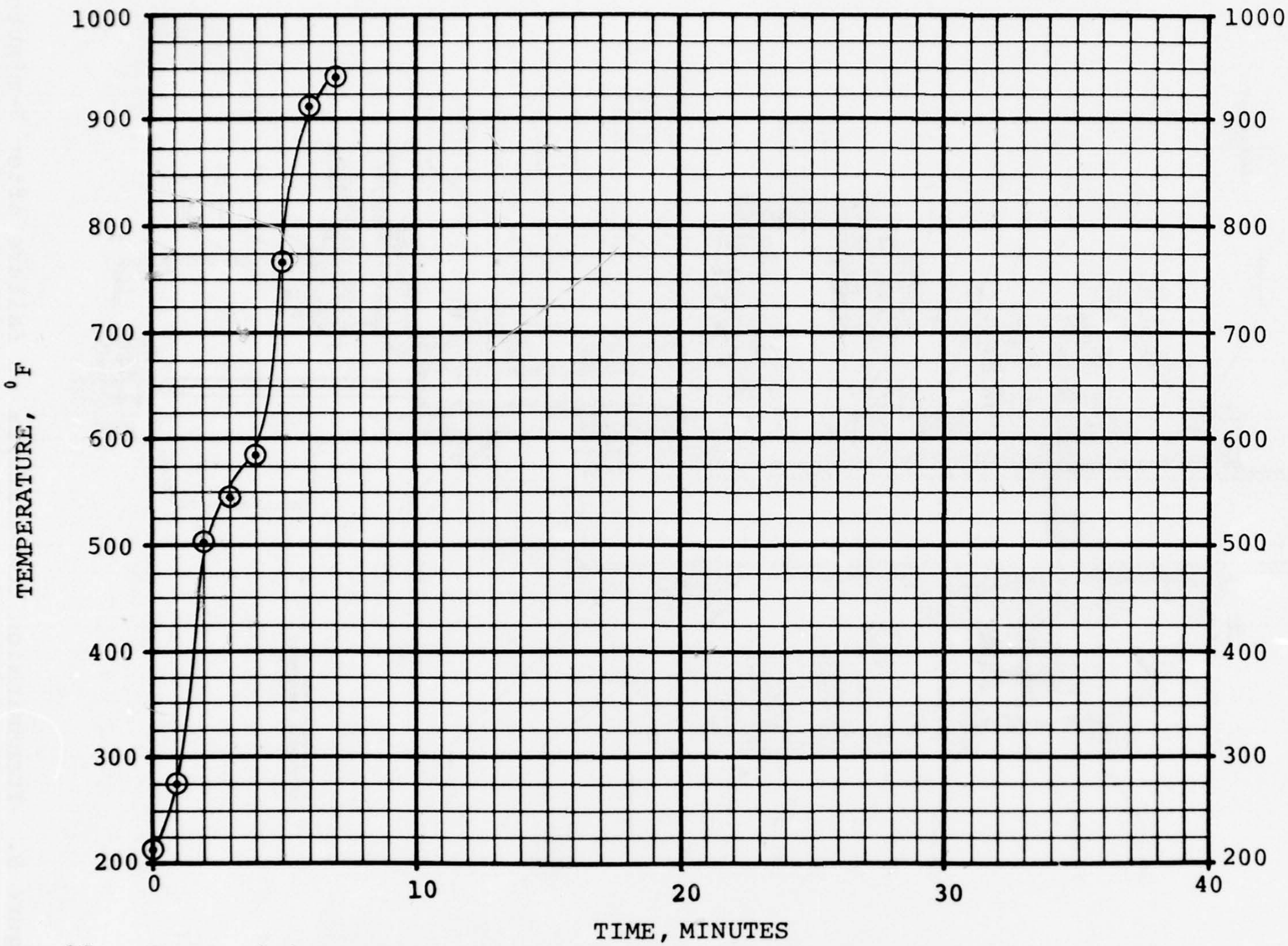

Figure 10. Input pinion tooth root temperatures during first loss-of-lube test of transmission number 1. (thermocouple no. 25)

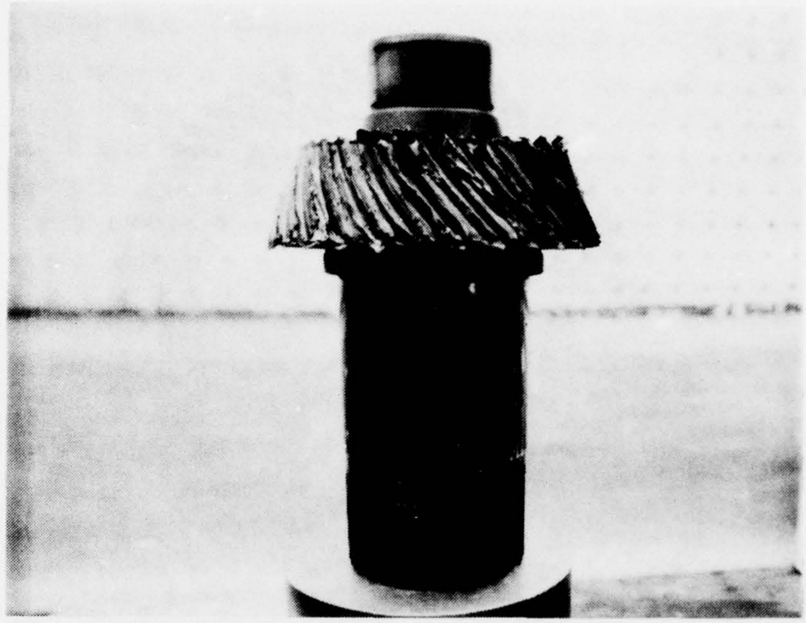

Figure 11. Main input pinion after 7-minute loss-of-lube test of transmission number 1.

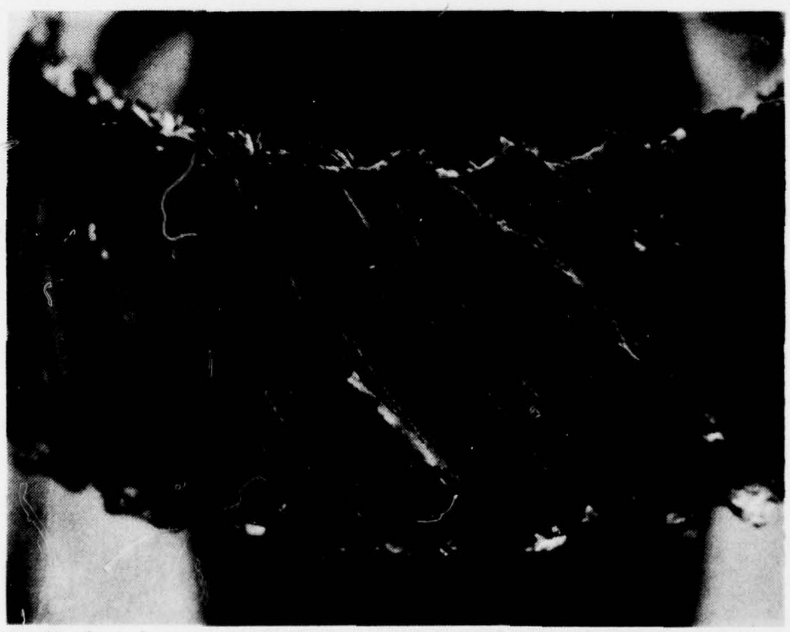

Figure 12. Main input pinion teeth after 7-minute loss-of-lube test of transmission number 1.

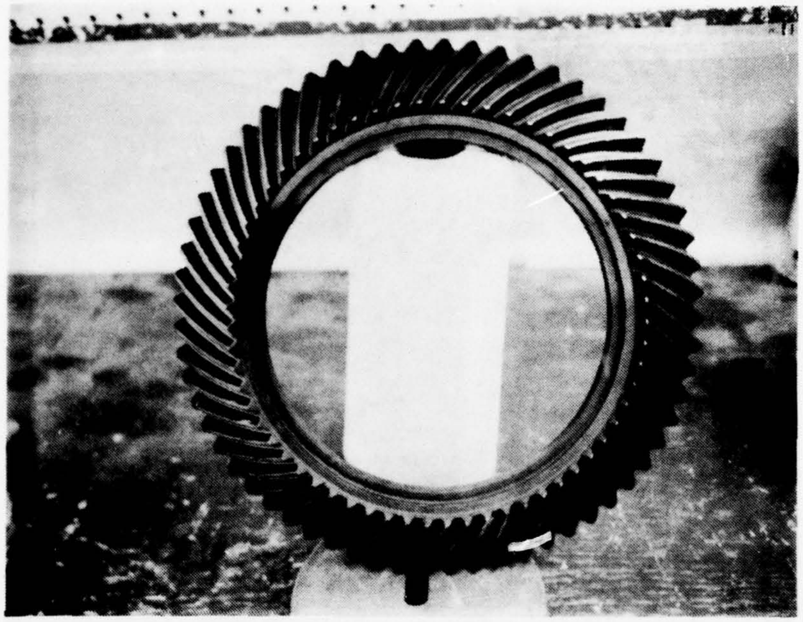

Figure 13. Main input gear after 7-minute loss-of-lube test of transmission number 1.

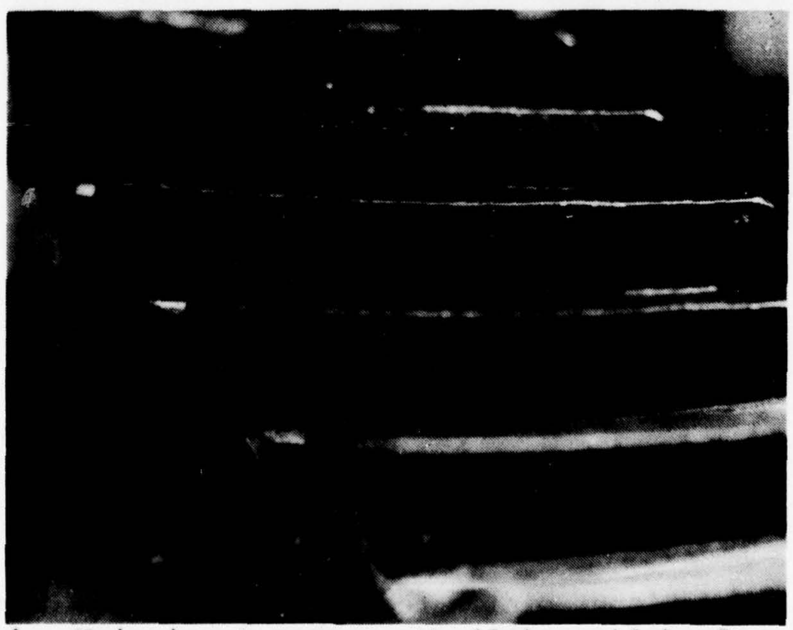

Figure 14. Main input gear teeth (drive side) after 7-minute loss-of-lube test of transmission number 1.

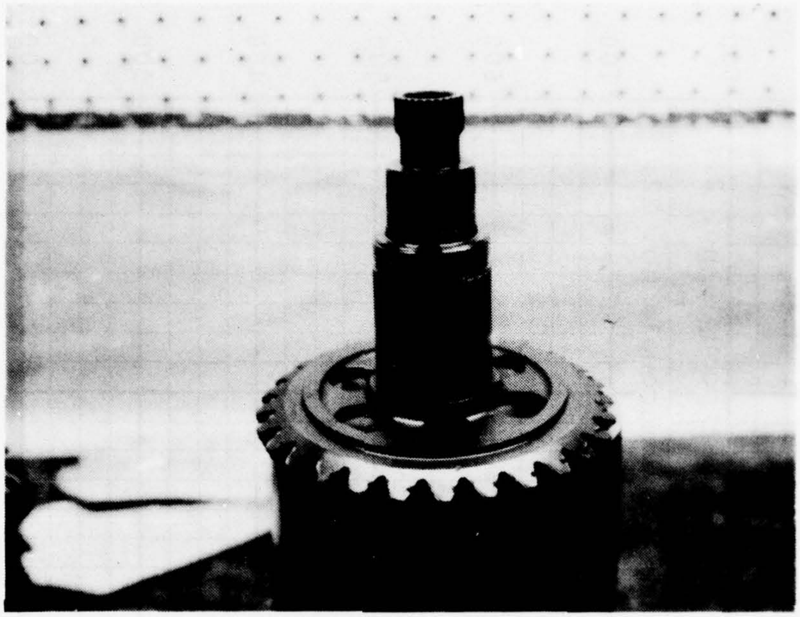

Figure 15. Fan accessory gear after 7-minute loss-of-lube test of transmission number 1.

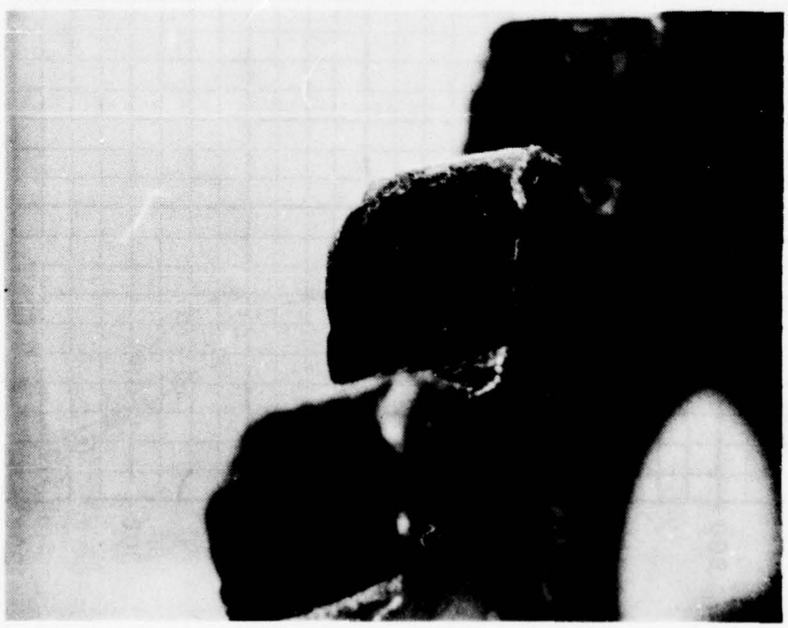

Figure 16. Fan accessory gear teeth (drive side) after 7-minute loss-of-lube test of transmission number 1.

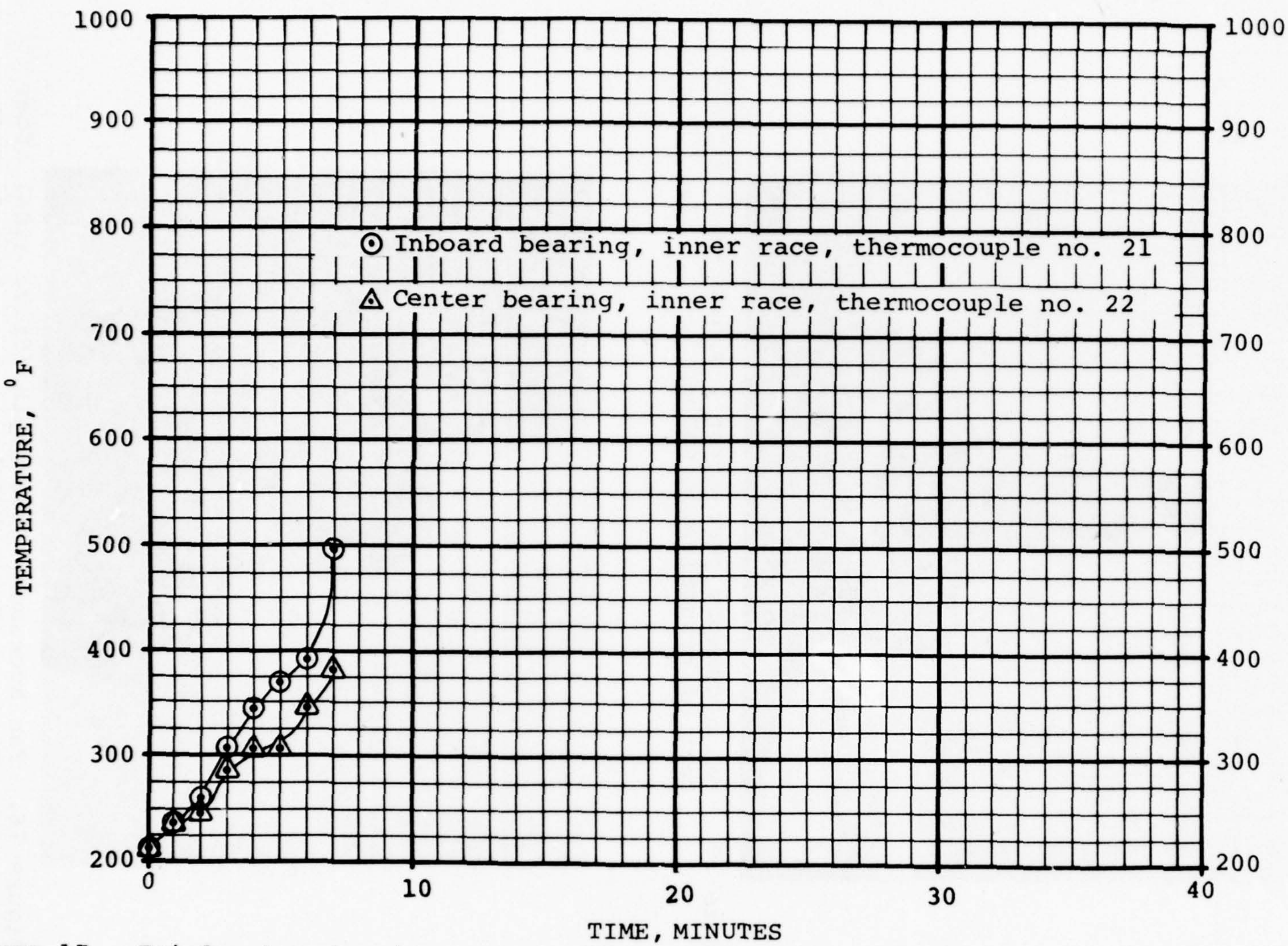

Figure 17. Triplex bearing inner race temperatures during first loss-of-lube test of transmission number 1.

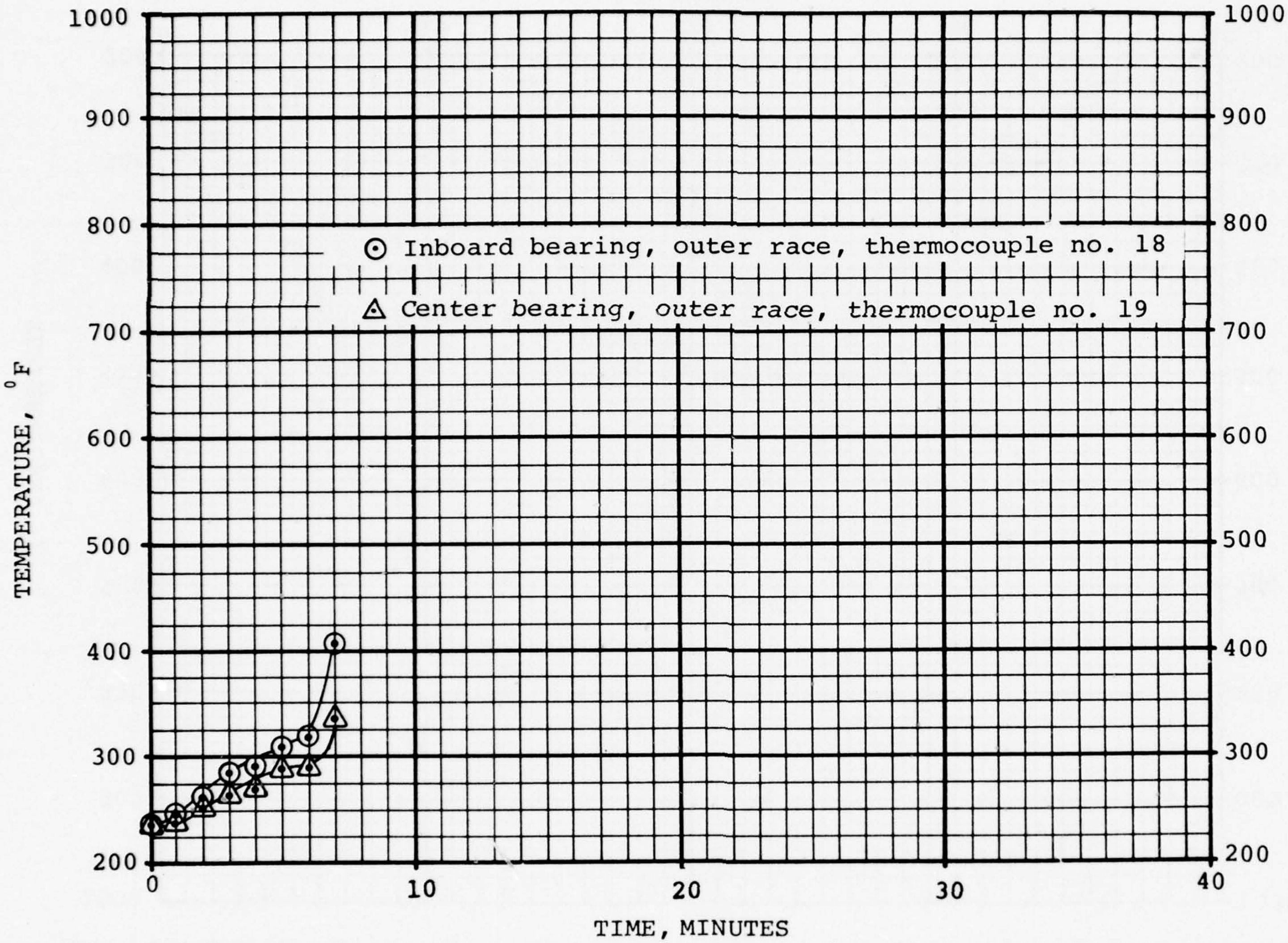

Figure 18. Triplex bearing outer race temperatures during first loss-of-lube test of transmission number 1.

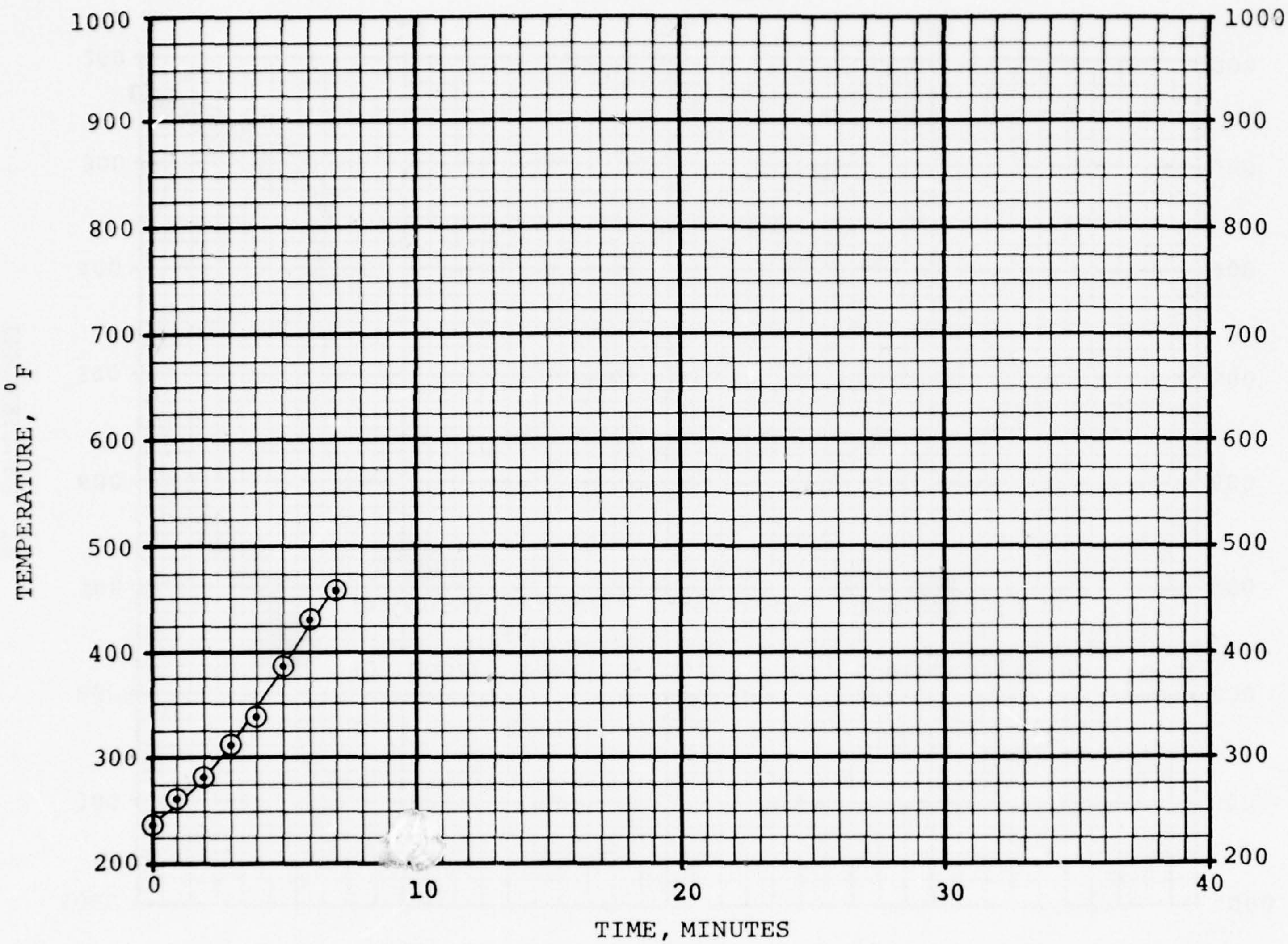

Figure 19. Input pinion roller bearing outer race temperatures during first loss-of-lube test of transmission number 1. (thermocouple no. 5)

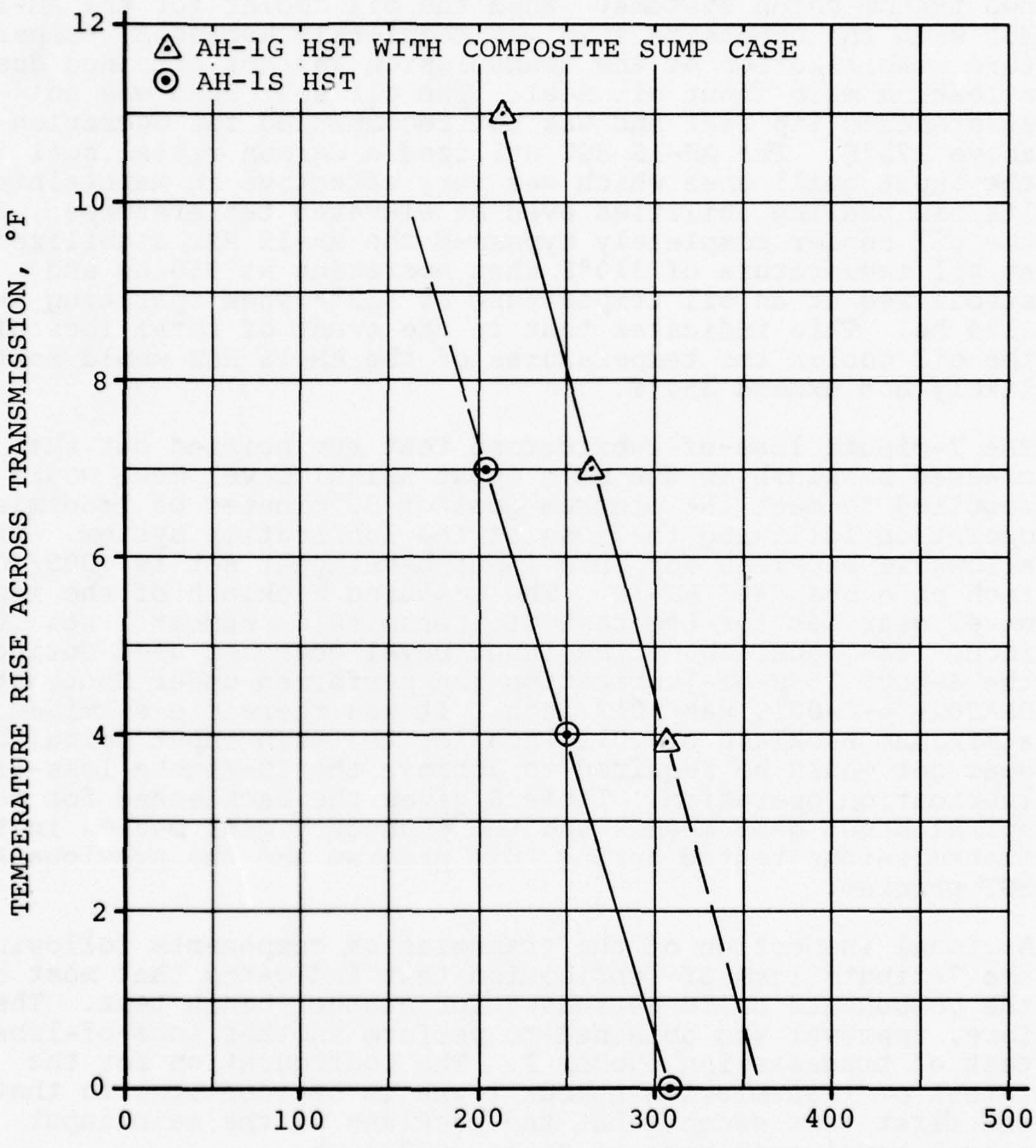

Figure 20. Oil cooler requirements of AH-1G HST with composite sump at 950 hp versus AH-1S HST at 950 hp.

two transmission systems. When the oil cooler for the AH-1G HST with the composite sump was completely bypassed, temperature stabilization of the transmission was not attained due to a leaking main input oil seal. The oil seal used was an elastomeric lip seal and was not recommended for operation above 275°F. The AH-1S HST utilized a carbon radial seal in the input quill area which was very effective in maintaining its oil sealing abilities even at elevated temperatures. With the oil cooler completely bypassed the AH-1S HST stabilized at an oil temperature of 310°F when operating at 950 hp and stabilized at an oil temperature of 323°F when operating at 1134 hp. This indicates that in the event of total loss of the oil cooler the temperatures of the AH-1S HST would most likely not exceed 350°F.

The 7-minute loss-of-lubrication test run pointed out that increased backlash in the main input spiral bevel mesh would be required to meet the program goal of 30 minutes of transmission operation following the loss of the lubrication system. The allowable backlash for this input bevel gear set is .005/.012 inch on a standard AH-1S. The measured backlash of the input bevel gear set for the test of transmission number 1 was .007 inch. The backlash of the input bevel gear set used during the 4-hour loss-of-lubrication run performed under Contract DAAJ02-74-C-0019 was .012 inch. It was therefore surmised that a minimum backlash of .012 inch for the main input spiral bevel gear set would be required to achieve the 30-minute loss-of-lubrication operation. Table 6 gives the backlashes for the spiral bevel gear meshes and the planetary gear meshes in the transmissions tested during this program and the previous AH-1G HST program.

A visual inspection of the transmission components following the 7-minute loss-of-lubrication test indicated that most of the components could be reused for another bench test. Therefore, approval was obtained to perform another loss-of-lube test of transmission number 1. The configuration for the retest of transmission number 1 was to be identical to that of the first test except that the backlash of the main input spiral bevel gear set was to be .012 inch.

6. AH-1S HST RETEST OF TRANSMISSION NUMBER 1

6.1 GENERAL OBJECTIVES

The retest of transmission number 1 was performed to demonstrate that the AH-1S High-Survivable Transmission number 1 configuration could meet the program goal of 30 minutes of loss-of-lube operation if the backlash of the main input spiral bevel gear set was increased to 0.12 inch.

6.2 RETEST OF TRANSMISSION NUMBER 1

6.2.1 Transmission Number 1 Retest Configuration

After the 7-minute loss-of-lubrication test, all of the transmission components were cleaned and the following parts were replaced so that the transmission could be reassembled for the retest program:

- Main input spiral bevel pinion
- Main input spiral bevel gear
- Main input gearshaft
- Main gearshaft support case
- Fan accessory gear
- Transmission main case
- Lubrication oil pump

Tables 1 and 6 define the transmission configuration for the retest of transmission number 1. Thermocouples were installed in the same locations as for the first test of transmission number 1 (reference Figure 2 and Table 2) and an additional thermocouple was installed in the out-of-mesh airstream of the main input spiral bevel gear mesh. An oil drainage system similar to the one used for the first test of transmission number 1 was installed; however, the oil cooler bypass was omitted since it would not be required during the retest program.

6.2.2 Description of Retest of Transmission Number 1

The reassembled transmission was green run according to the load and speed schedule of Table 3 in order to meet the following specific objectives:

TABLE 6. BACKLASH DATA FOR LOSS-OF-LUBE TESTING

Gear Mesh	Allowable B/L (in.)	AH-1G HST B/L (in.)	AH-1S HST B/L (in.) XMSN No. 1	Retest XMSN No. 1	XMSN No. 2	4th Test
Main input spiral bevel	.005/.012	.012	.007	.012	.012	.012
Acc fan drive spiral bevel	.005/.013	-	.008	.013	.012	.012
Tail rotor drive spiral bevel	.004/.010	.009	.007	.009	.009	.009
Hydraulic pump & tach drive spiral bevel	.014/.020	-	.020	.022	.019	.0185
Lwr. sun-planet spur	.0035/.0065	.0035/.0065*	.0058	.0058	.0126	.0115
Lwr. planet ring spur	.0035/.0065	.0035/.0065*	.0046	.0046	.0115	.0117
Upper sun-planet spur	.0035/.0065	.0035/.0065*	.0058	.0058	.0113	.0035/.0065*
Upper ring-planet spur	.0035/.0065	.0035/.0065*	.0046	.0046	.0112	.0035/.0065*

* Dimensional inspections of these planetary gears were not performed.

- To verify proper assembly and to give the new parts a break-in period.

- To check out all instrumentation.

No thermal testing was conducted during the retest program. A loss-of-lube test was performed according to the load and speed schedule of Table 5 to determine the response of the transmission to loss of the bypass valve and/or the lower part of the sump which would result in the loss of the main oil supply.

6.3 RESULTS OF RETEST OF TRANSMISSION NUMBER 1

6.3.1 Results of Green Run for Retest of Transmission Number 1

The green run was completed successfully and the instrumentation was found to be performing satisfactorily. Only the main input spiral bevel gear set and the tail rotor drive spiral bevel gear set were inspected after the green run. Both gear sets exhibited normal gear tooth wear patterns. Although the main input spiral bevel gear mesh backlash had been increased to .012 inch, the gear tooth wear pattern was still within acceptable limits.

6.3.2 Results of Loss-of-Lube Retest of Transmission Number 1

The loss-of-lube retest of transmission number 1 was performed according to the load and speed schedule of Table 5. The test transmission was operated at 950 input horsepower (84 percent of MCP) under normal lubrication conditions until the inlet oil temperatures stabilized at 230°F. Then, with the transmission still operating at 950 input horsepower (30 hp through the tail rotor, lift and bending loads applied to the main rotor mast), the oil was drained from the transmission in a manner similar to that of the first test of transmission number 1. After complete loss of the main oil supply, the transmission continued to operate for 21 minutes before a failure of lower planetary stage occurred. At failure, the lower ring gear temperature was in excess of 950°F. (The temperature recorder had a mechanical stop which prevented recording temperatures above 950°F.) Figures 21 through 33 show temperature plots of various components during the 21-minute loss-of-lube test and Figure 34 shows transmission temperatures at failure.

Following the 21-minute loss-of-lube test, the transmission was disassembled for a post-run inspection. Figures 35 through 50 show some of the disassembled components. The planetary pinions of the lower planetary stage were oblong and deformed. The teeth had softened and were flattened or stripped from the pinions. The planetary roller bearing cages were still recognizable but the tangs had been pressed into the center ring

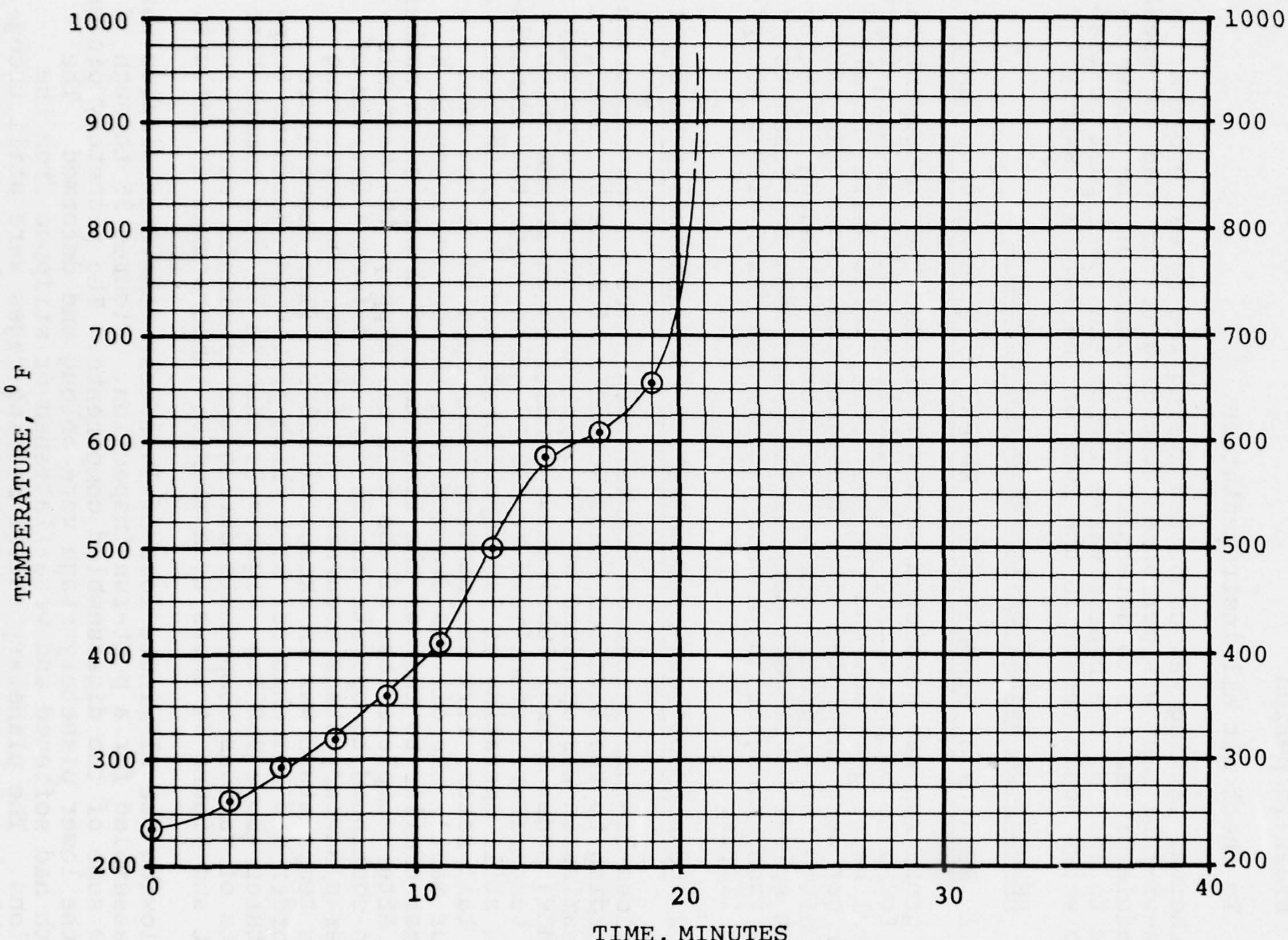

Figure 21. Lower ring gear tooth root temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 13)

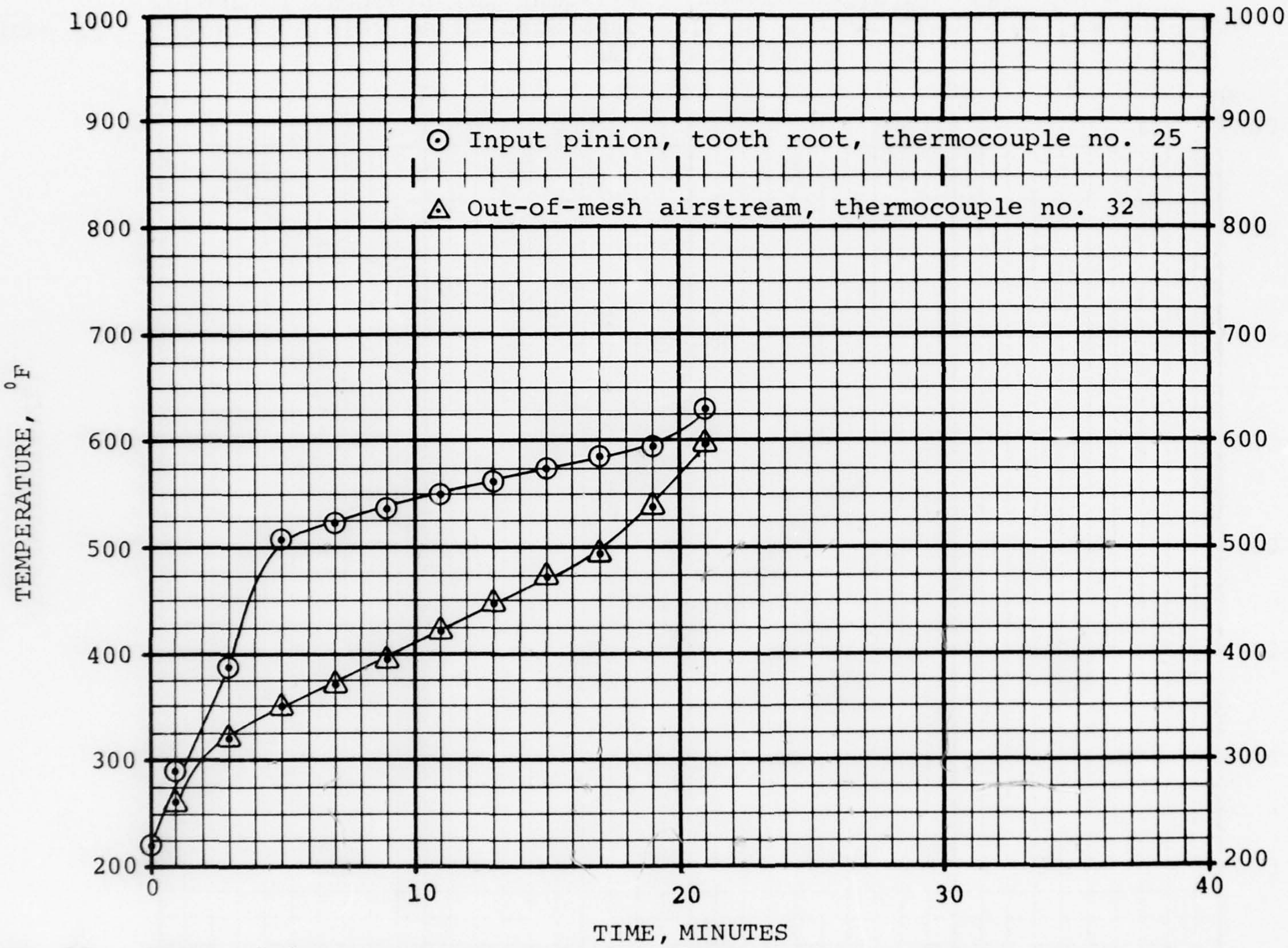

Figure 22. Input pinion temperatures during 21-minute loss-of-lube retest of transmission number 1.

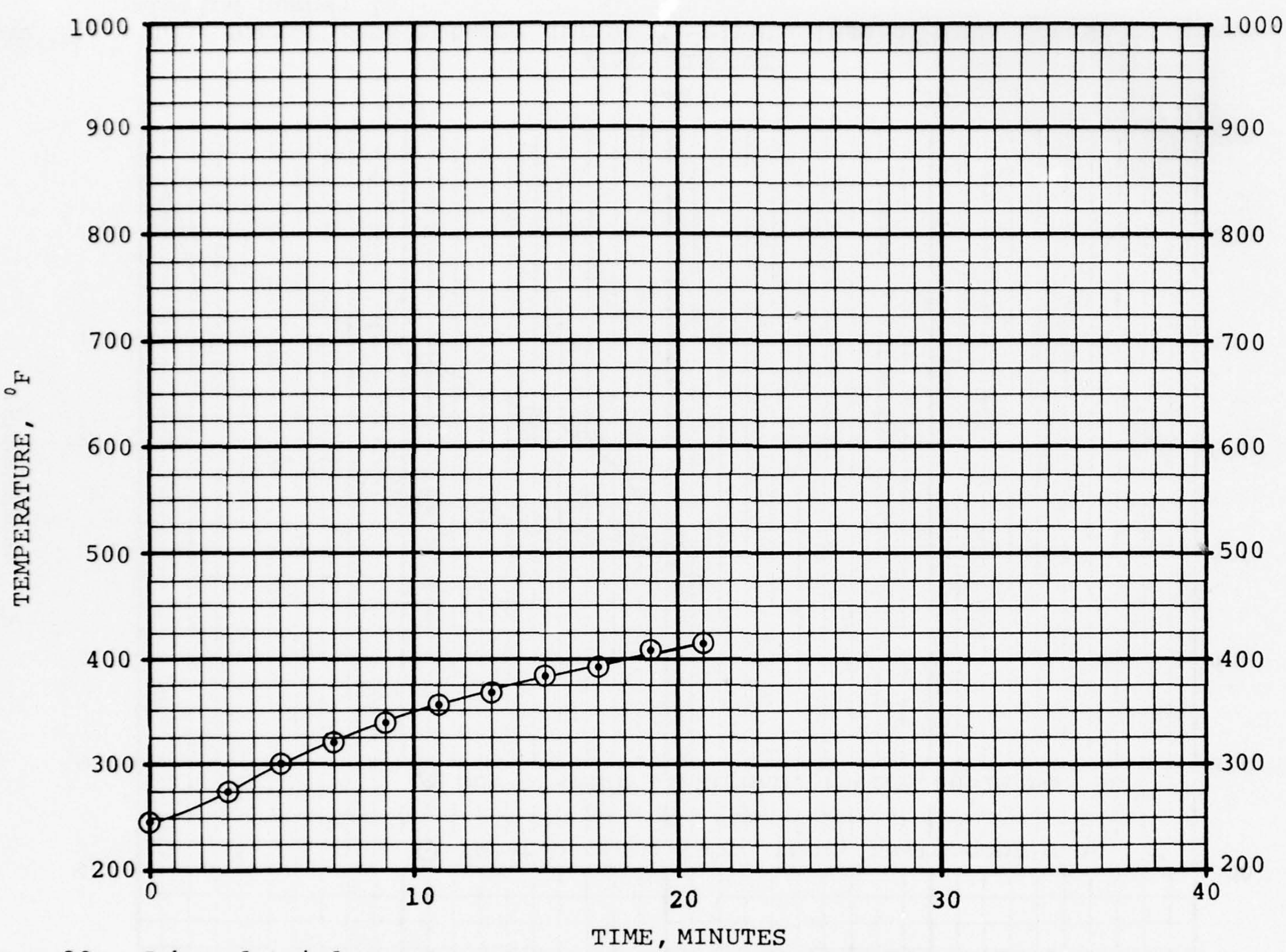

Figure 23. Inboard triplex outer race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 18)

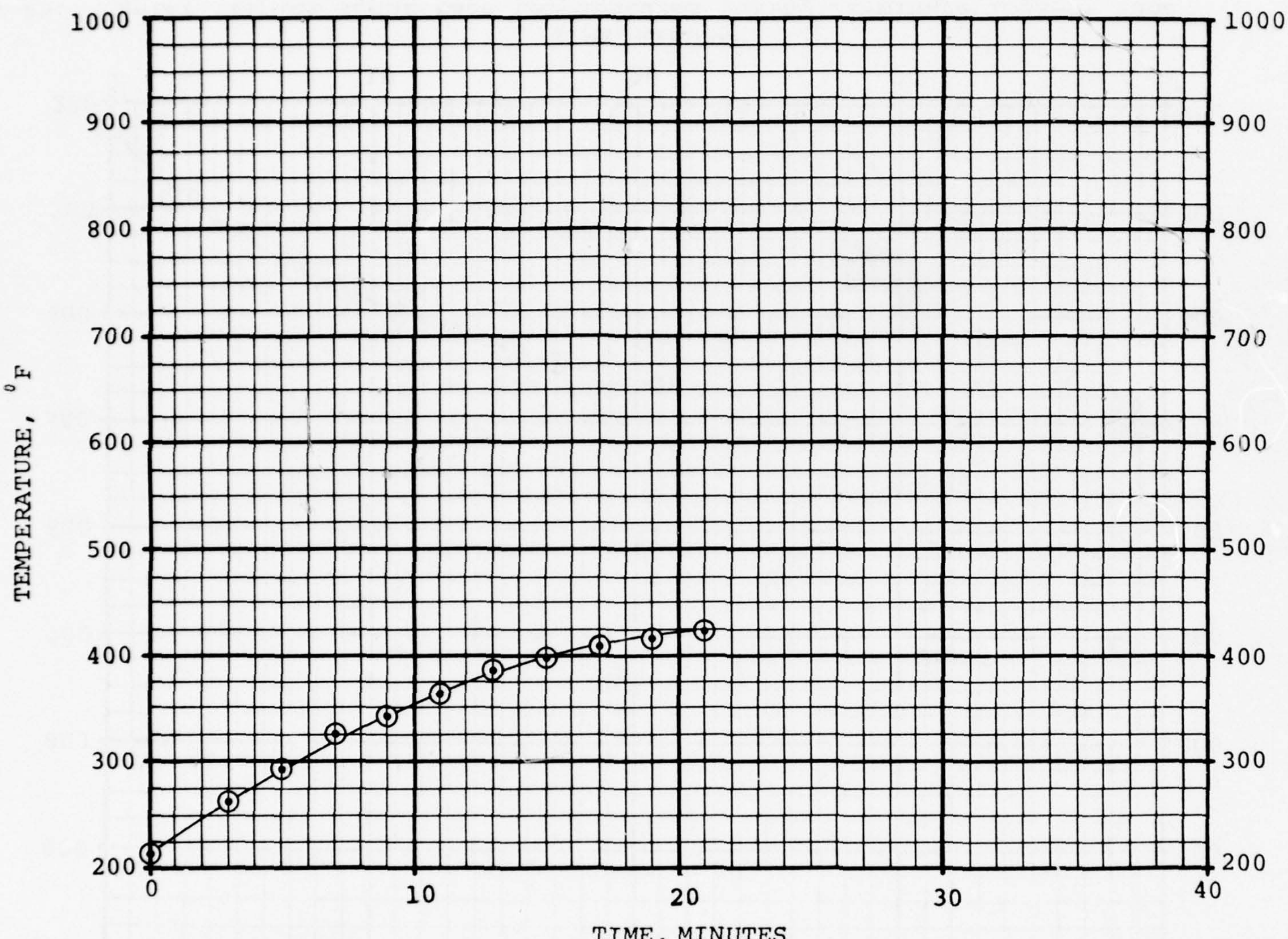

Figure 24. Inboard triplex inner race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 21)

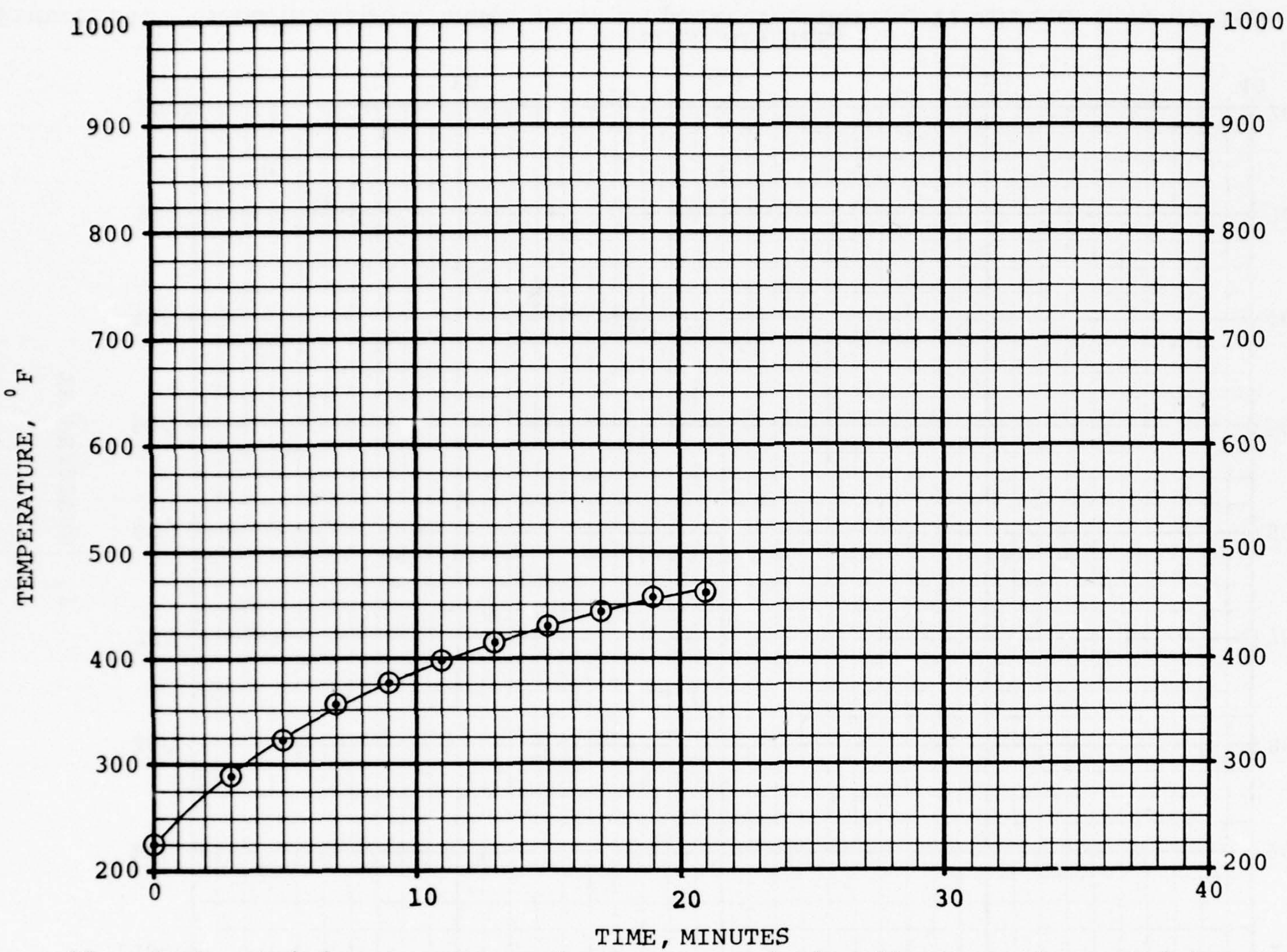

Figure 25. Center triplex inner race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 22)

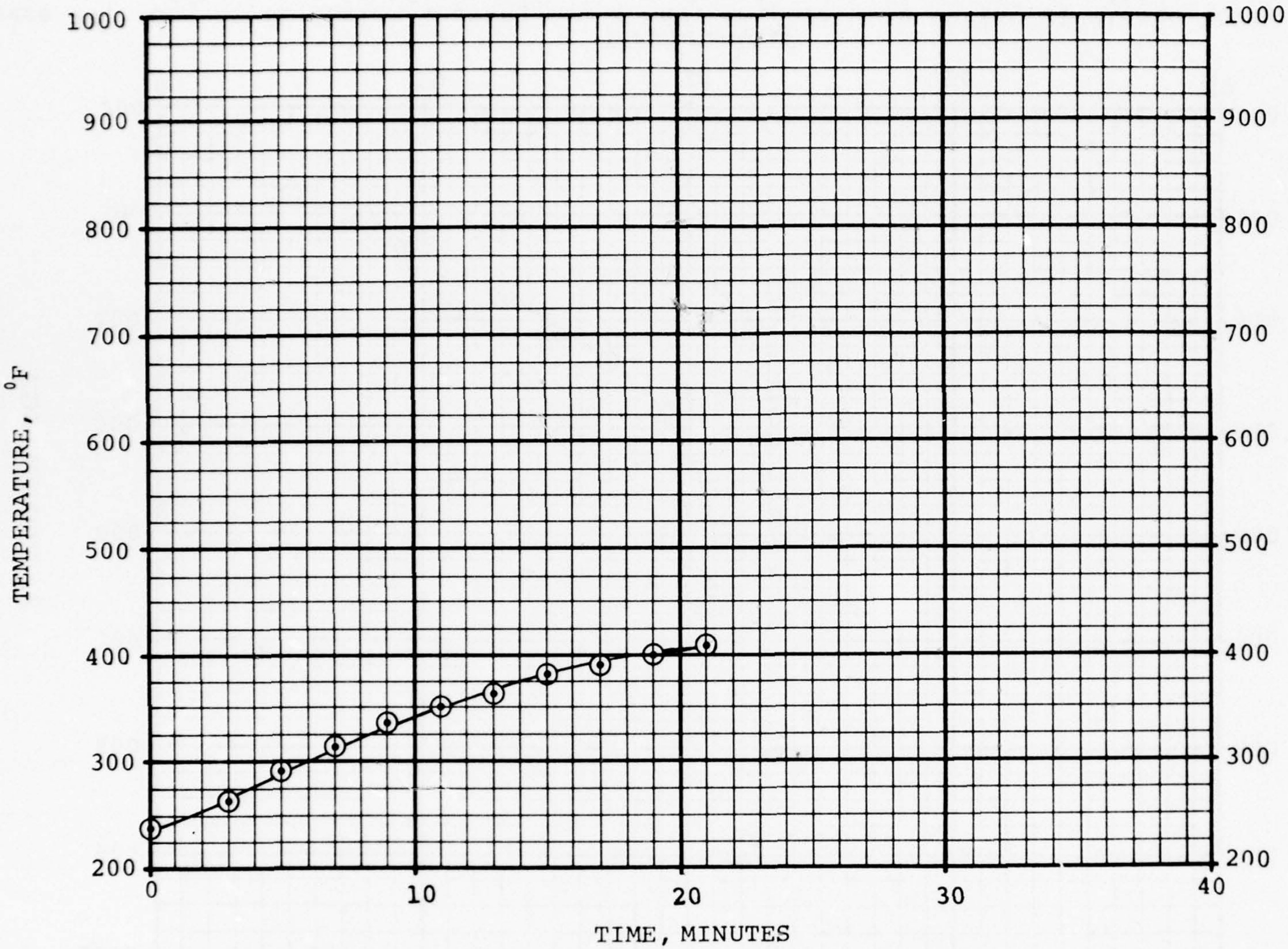

Figure 26. Center triplex outer race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 19)

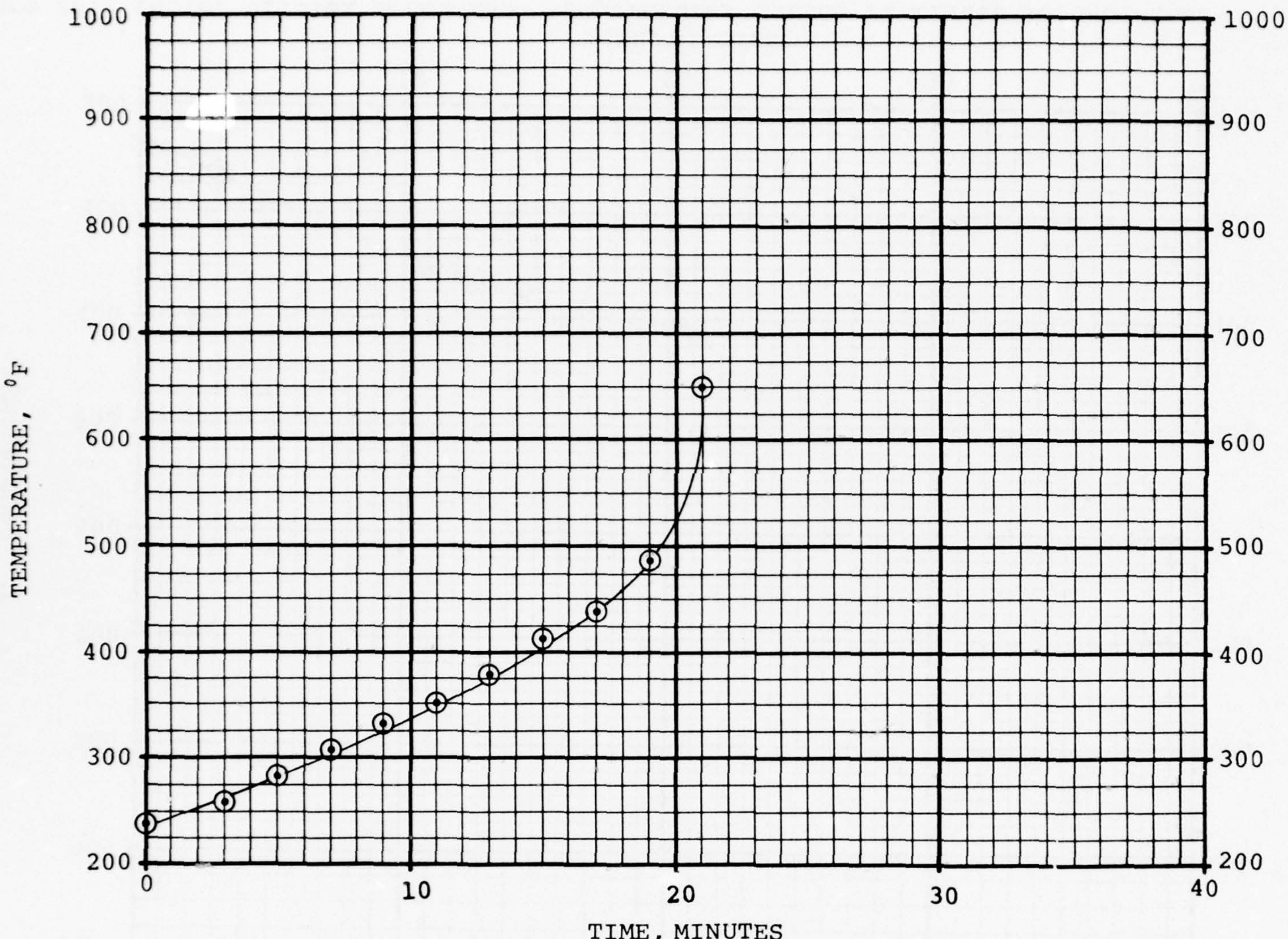

Figure 27. Gearshaft duplex bearing outer race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 4)

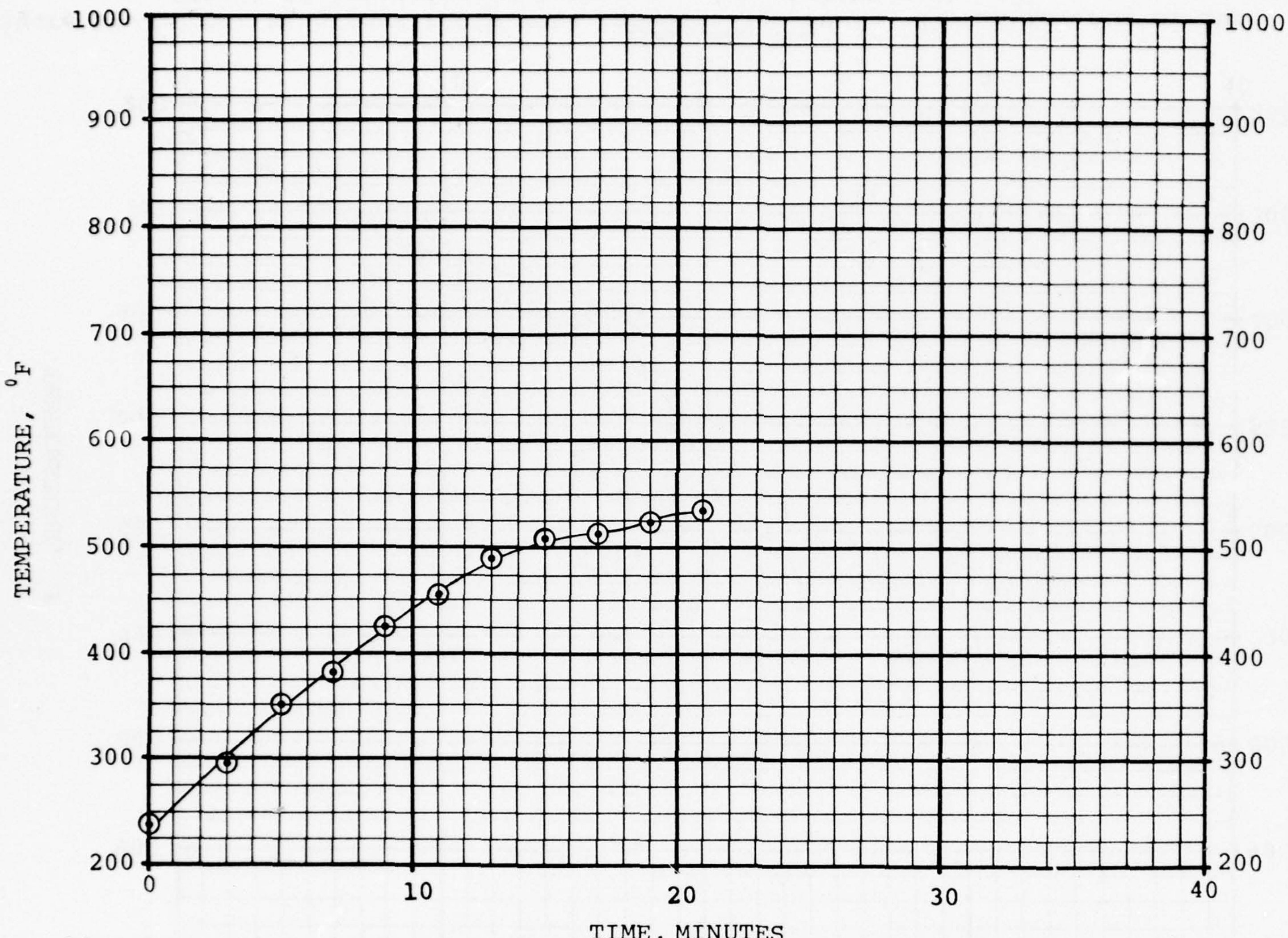

Figure 28. Input pinion roller bearing outer race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 5)

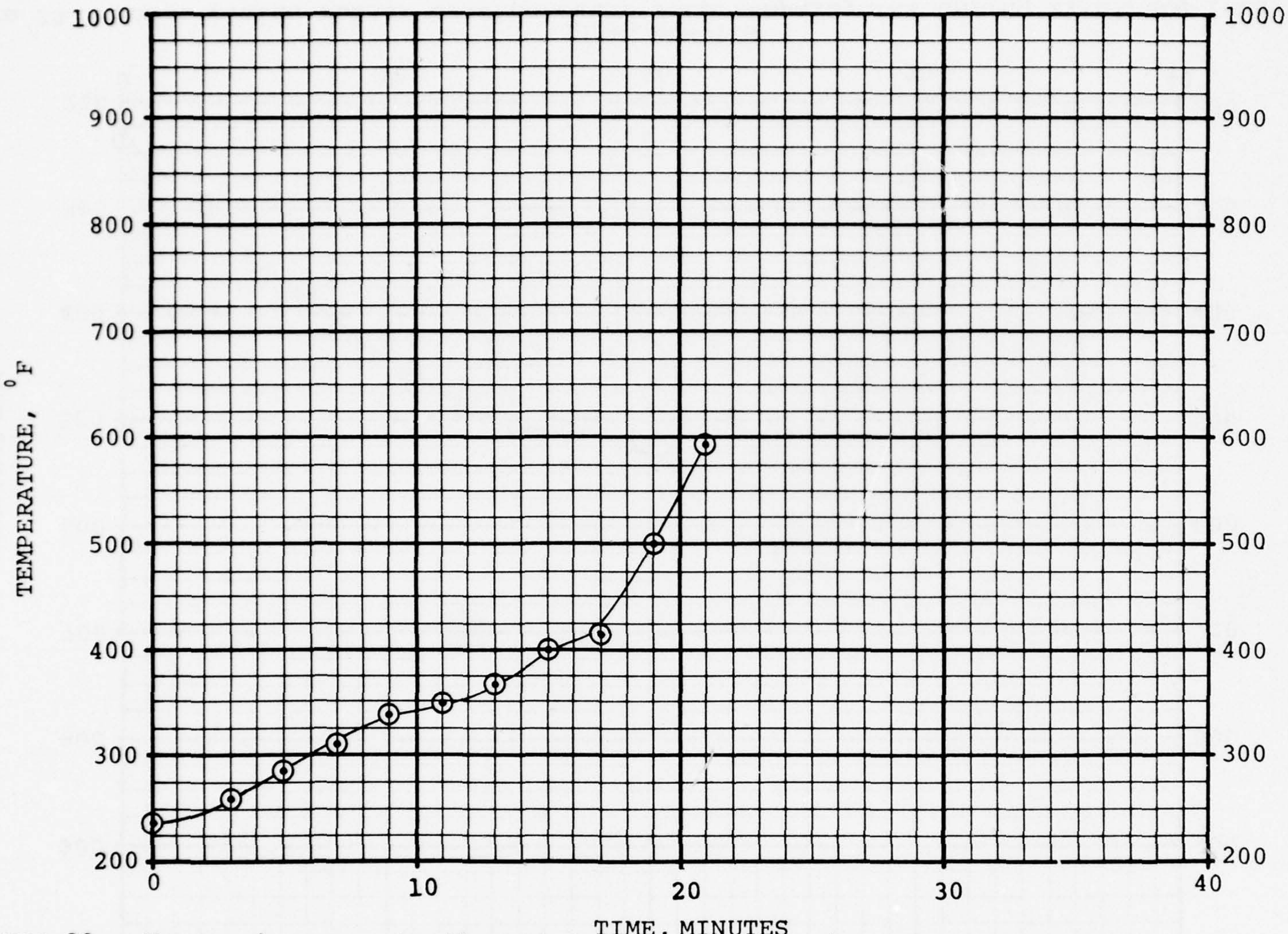

Figure 29. Upper ring gear tooth root temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 12)

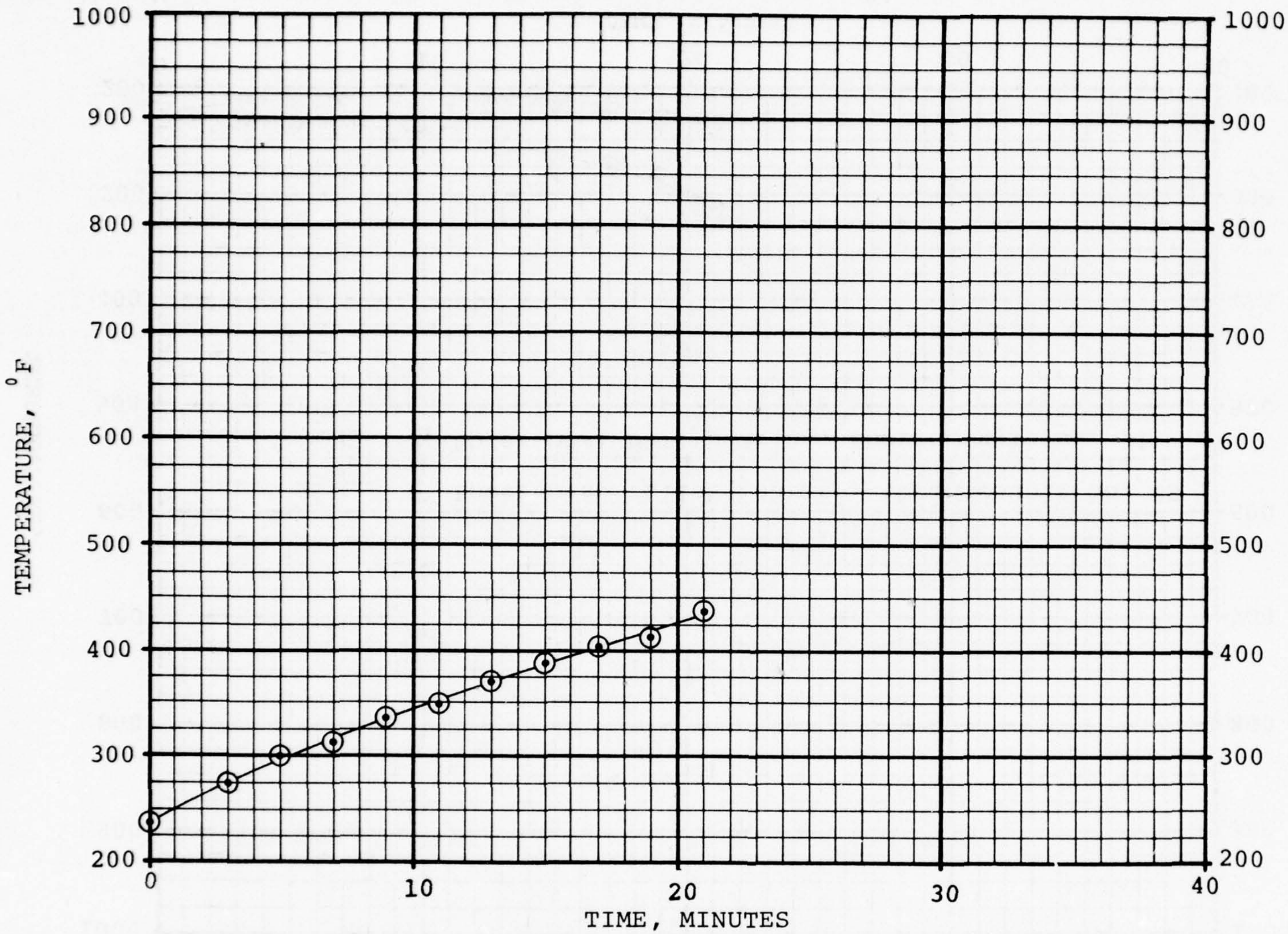

Figure 30. Gearshaft roller bearing outer race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 6)

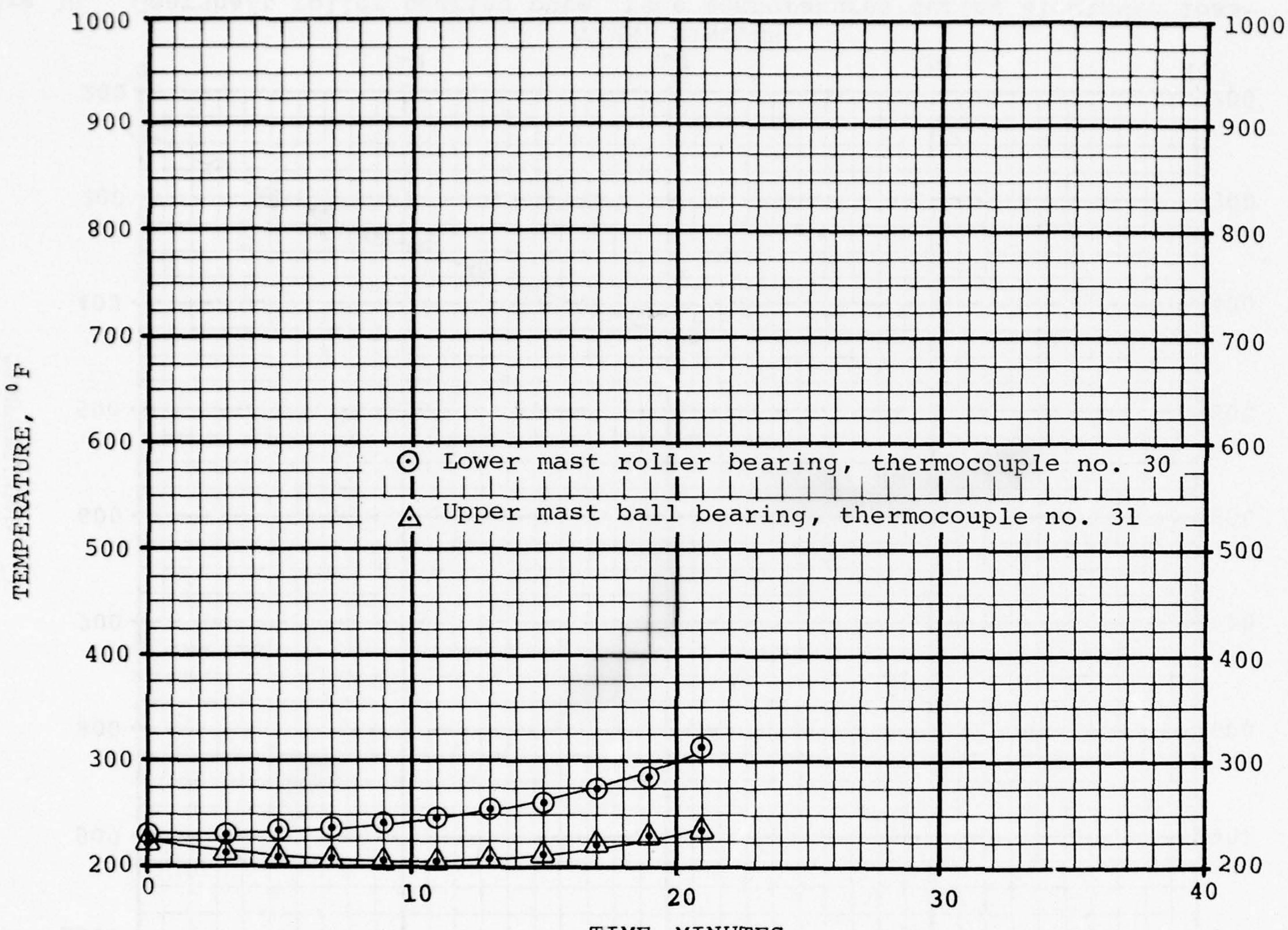

Figure 31. Mast bearings outer race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple nos. 31 and 30)

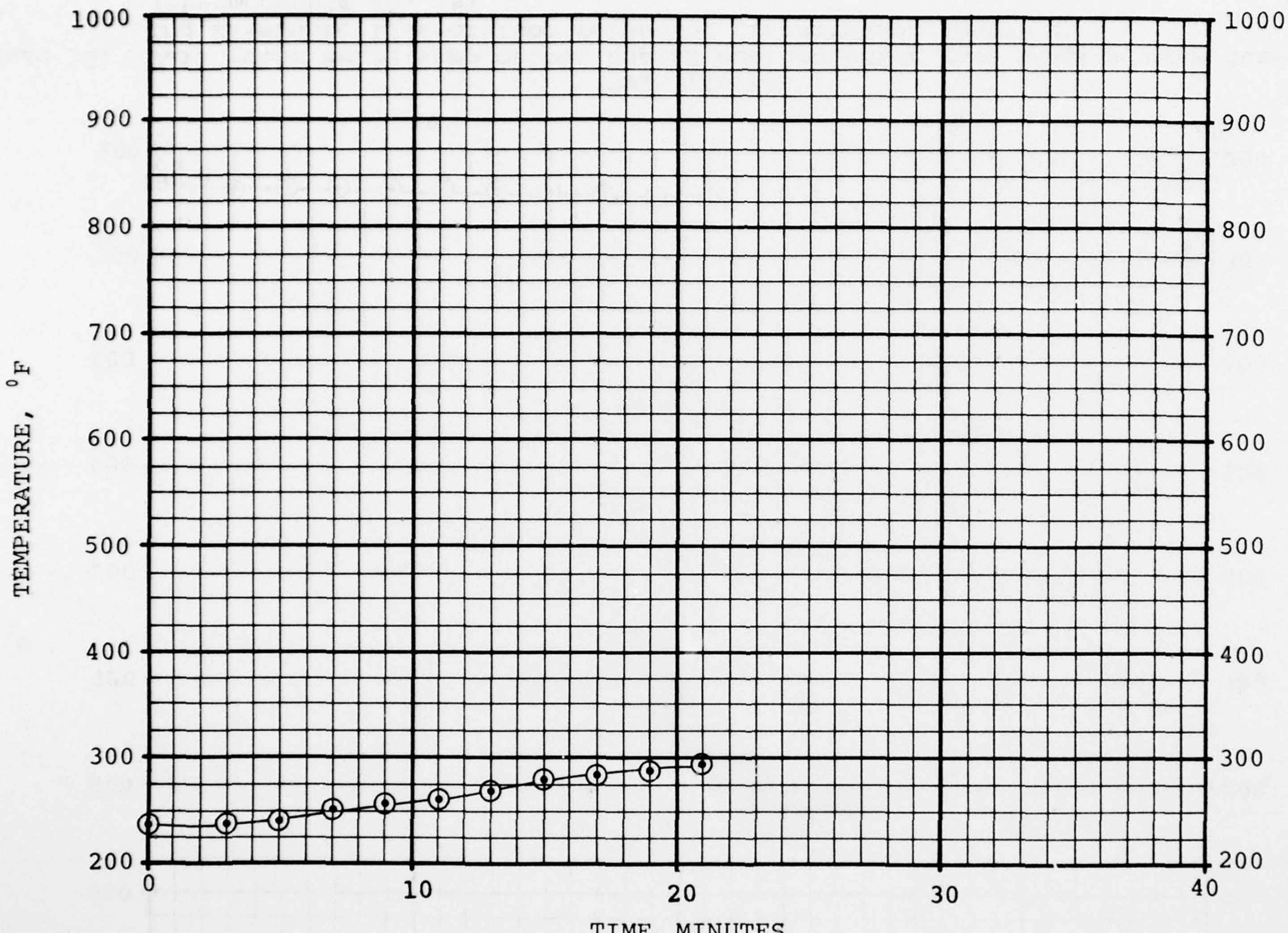

Figure 32. Tail rotor drive sump input duplex bearing outer race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 14)

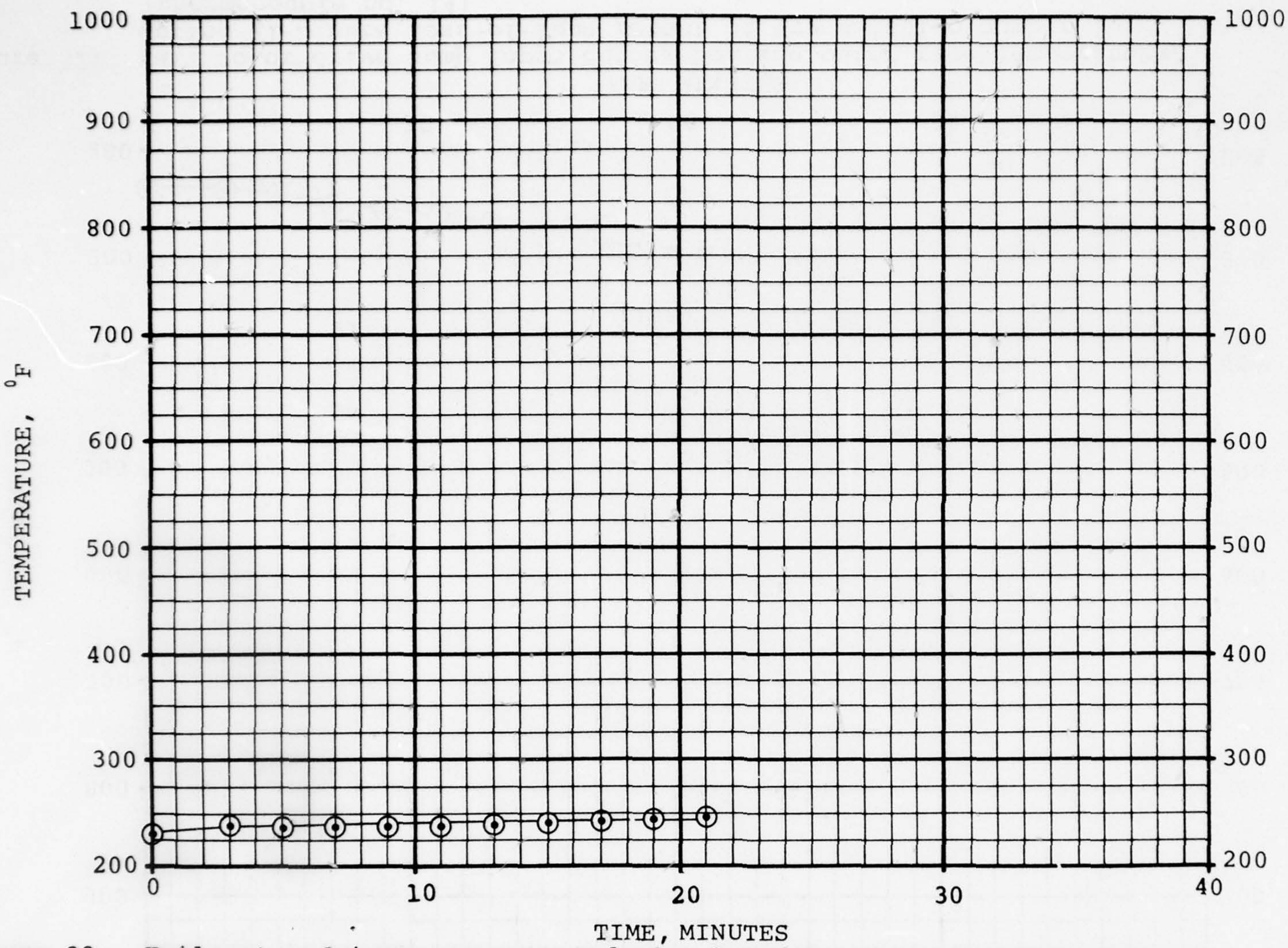

Figure 33. Tail rotor drive sump output duplex bearing outer race temperatures during 21-minute loss-of-lube retest of transmission number 1. (thermocouple no. 16)

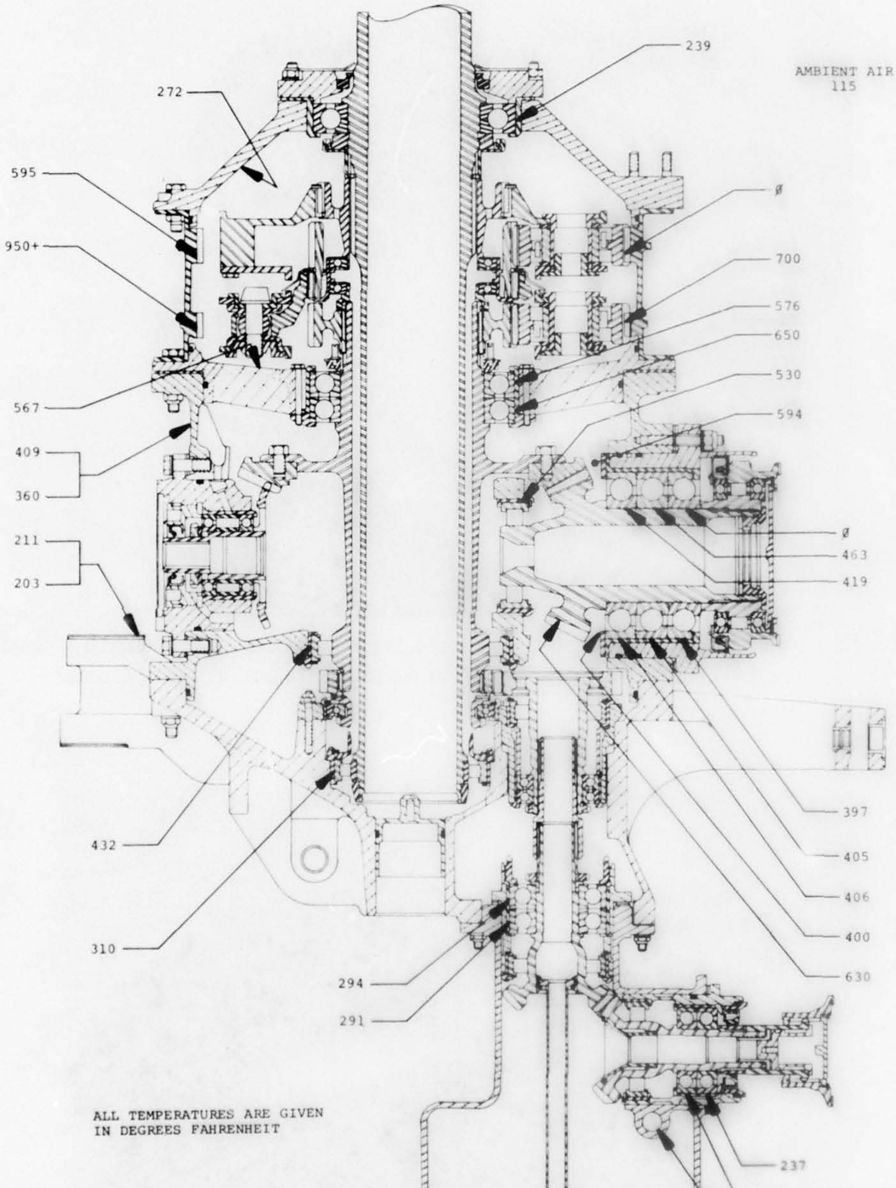

Figure 34. Transmission temperatures after 21-minute loss-of-lube retest of transmission number 1.

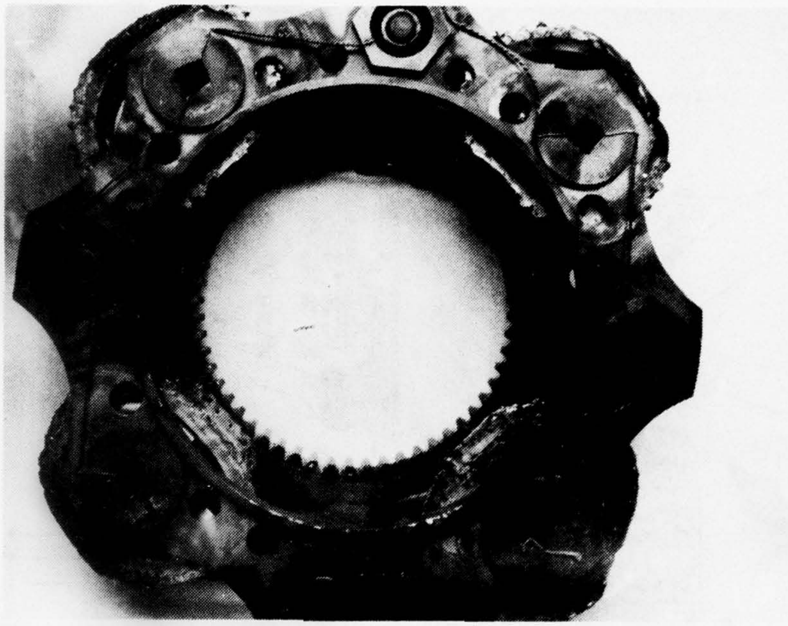

Figure 35. Lower planetary assembly after 21-minute loss-of-lube retest of transmission number 1.

Figure 36. Lower planetary pinion, bearing inner race, rollers, roller guides, and retainer after 21-minute loss-of-lube retest of transmission number 1.

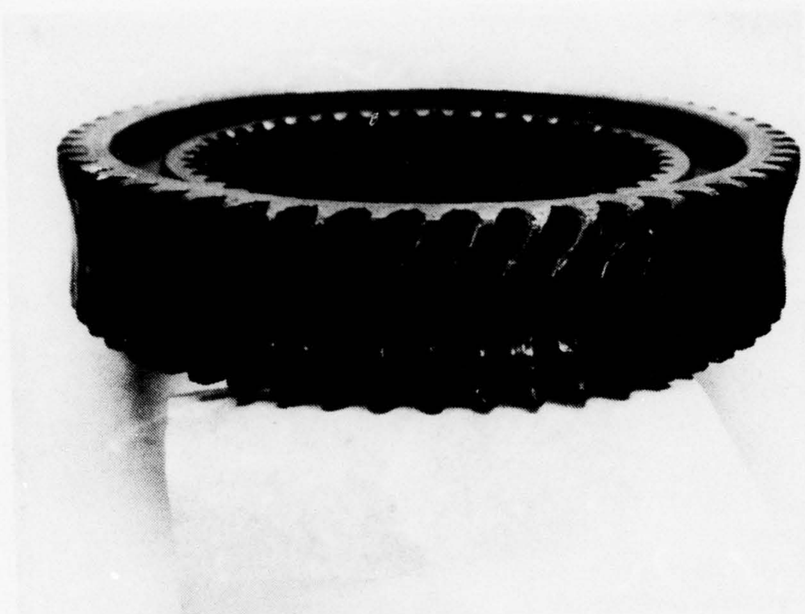

Figure 37. Lower sun gear after 21-minute loss-of-lube retest of transmission number 1.

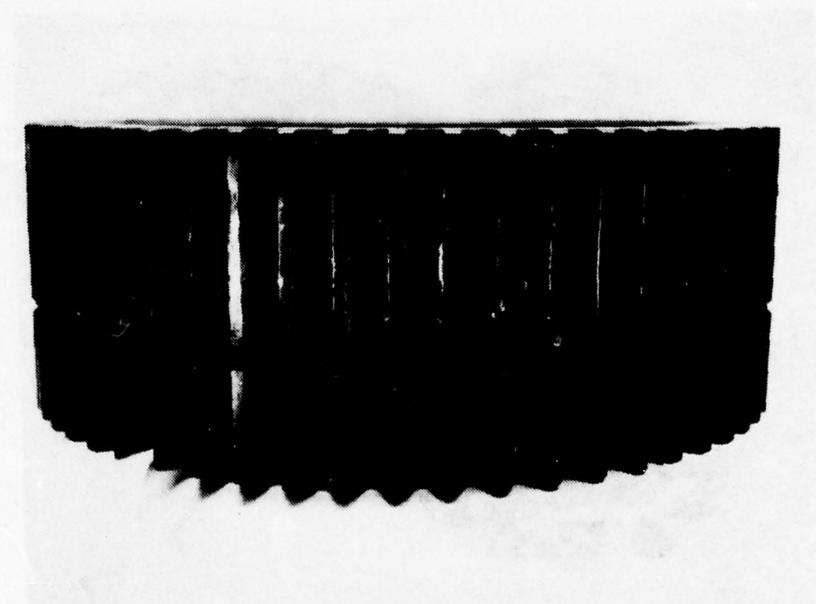

Figure 38. Upper sun gear after 21-minute loss-of-lube retest of transmission number 1.

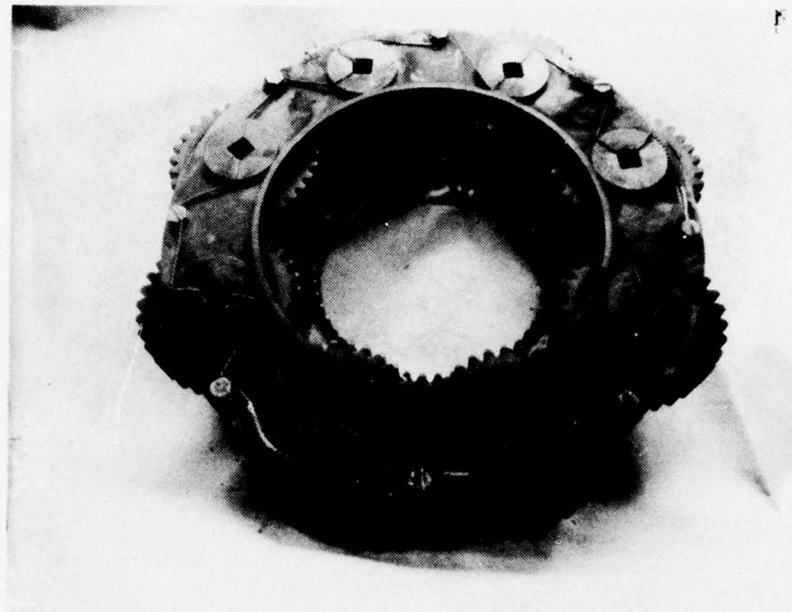

Figure 39. Upper planetary assembly after 21-minute loss-of-lube retest of transmission number 1.

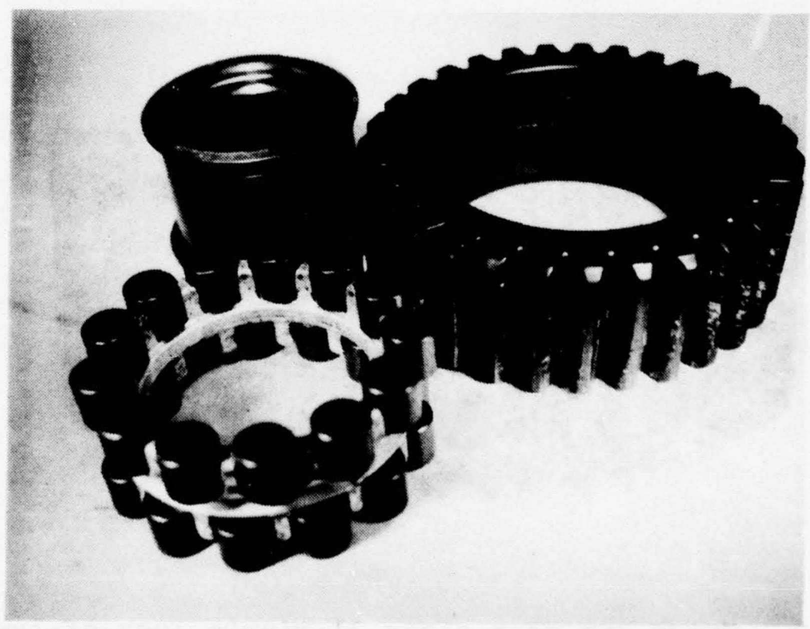

Figure 40. Upper planetary pinion, bearing inner race, rollers, roller guides, and retainer after 21-minute loss-of-lube retest of transmission number 1.

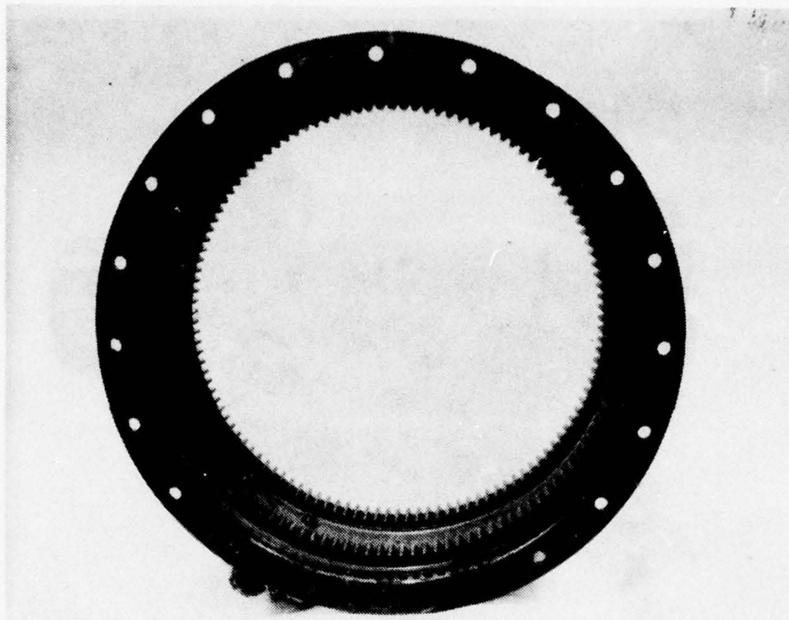

Figure 41. Ring gear case after 21-minute loss-of-lube retest of transmission number 1.

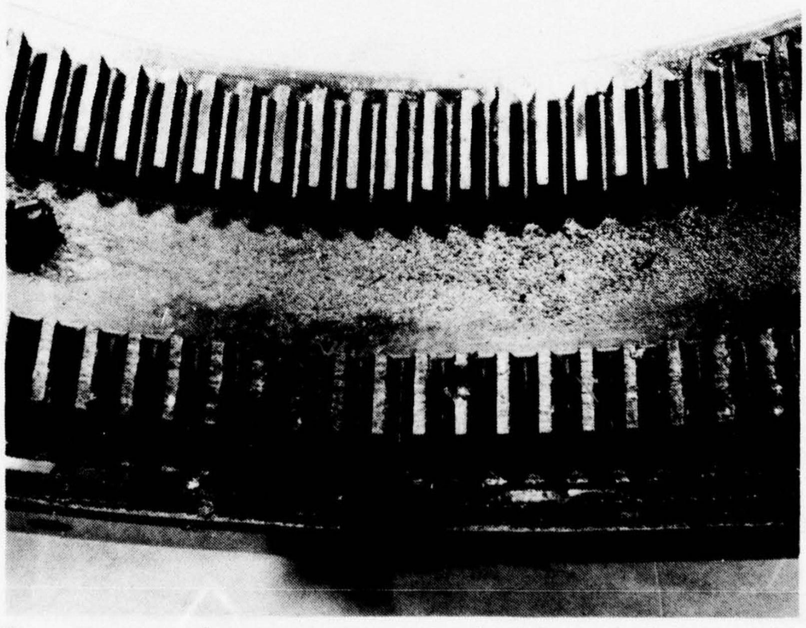

Figure 42. Upper ring gear teeth (top) and lower ring gear teeth (bottom) after 21-minute loss-of-lube retest of transmission number 1.

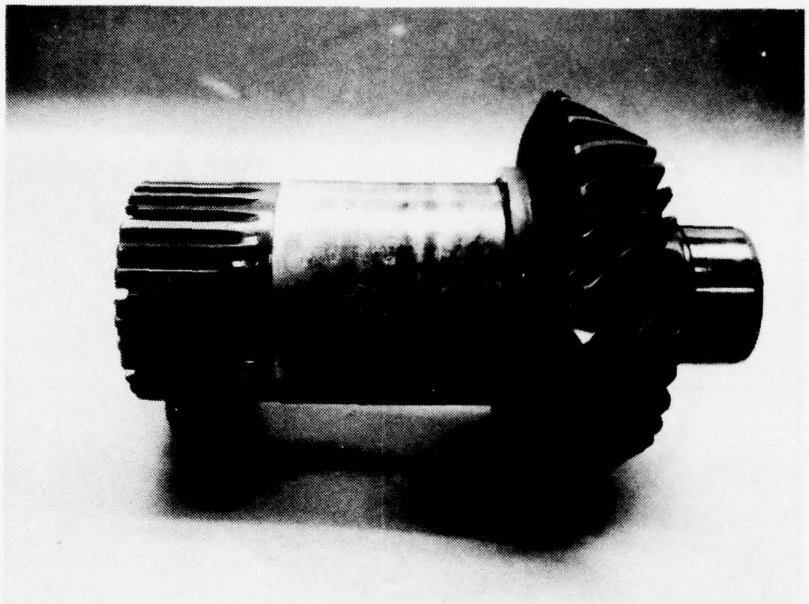

Figure 43. Main input pinion after 21-minute loss-of-lube retest of transmission number 1.

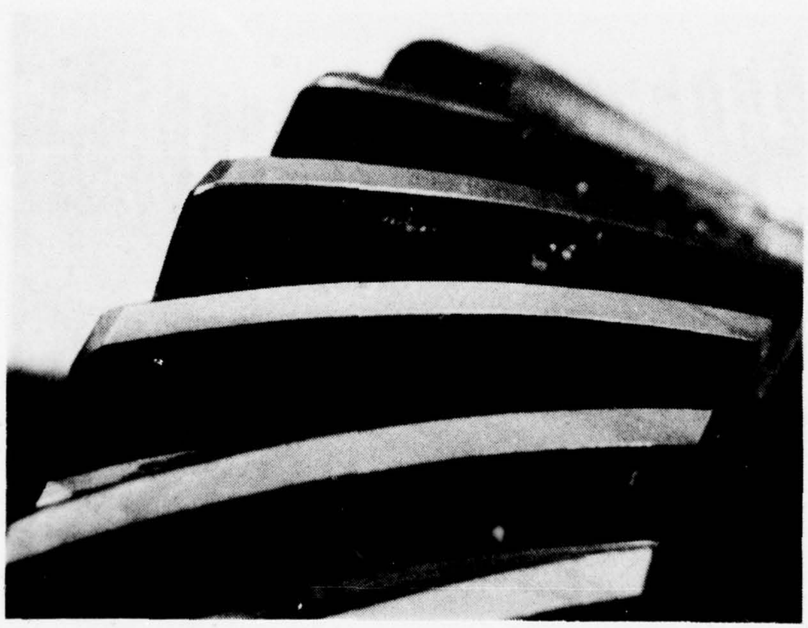

Figure 44. Main input pinion teeth (drive side) showing light scoring after 21-minute loss-of-lube retest of transmission number 1.

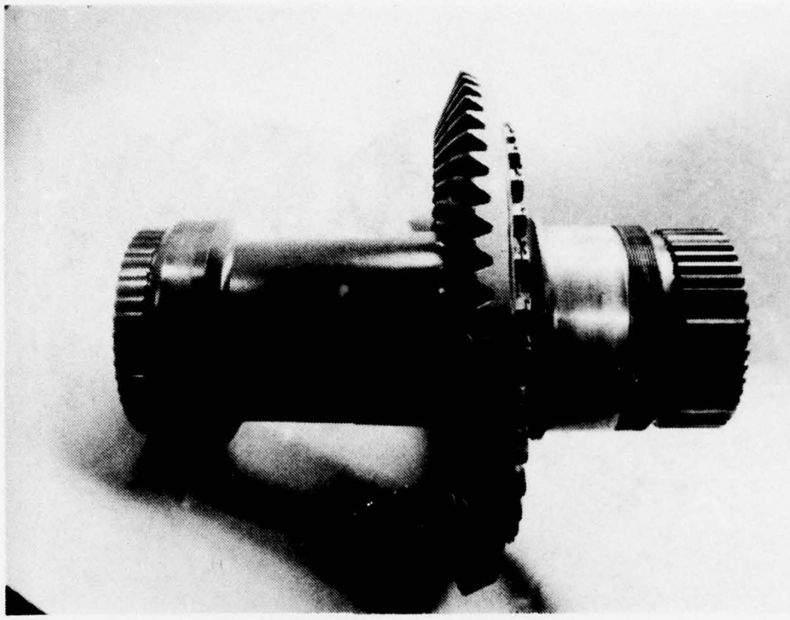

Figure 45. Main input gear and gearshaft after 21-minute loss-of-lube retest of transmission number 1.

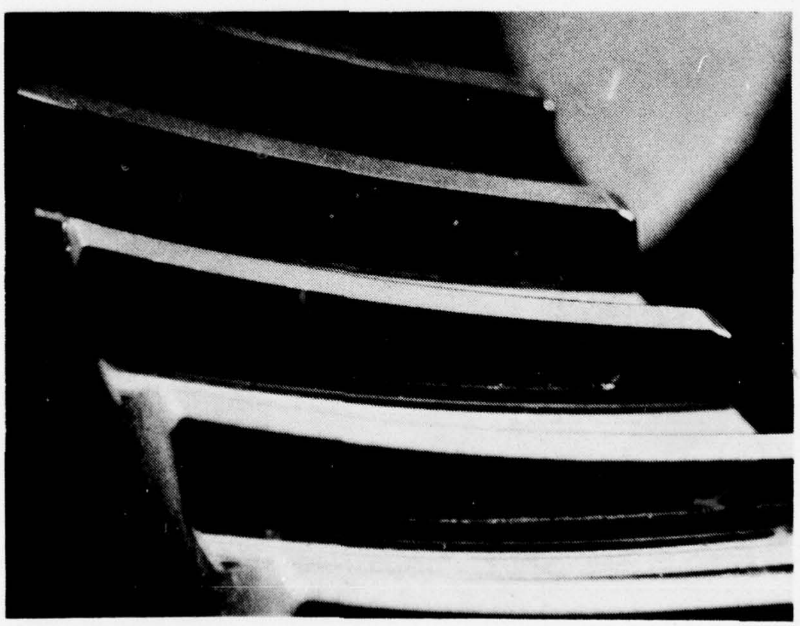

Figure 46. Main input gear teeth (drive side) showing light scoring after 21-minute loss-of-lube retest of transmission number 1.

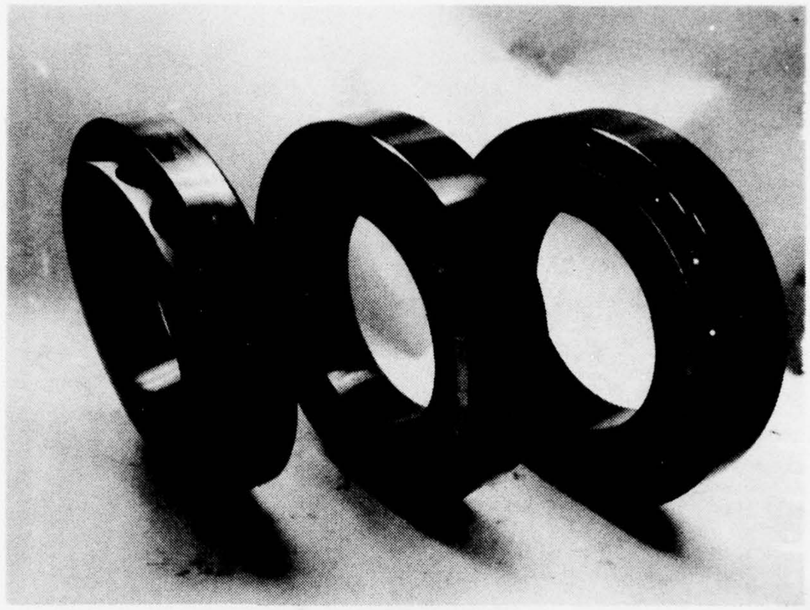

Figure 47. Main input triplex bearing after 21-minute loss-of-lube retest of transmission number 1.

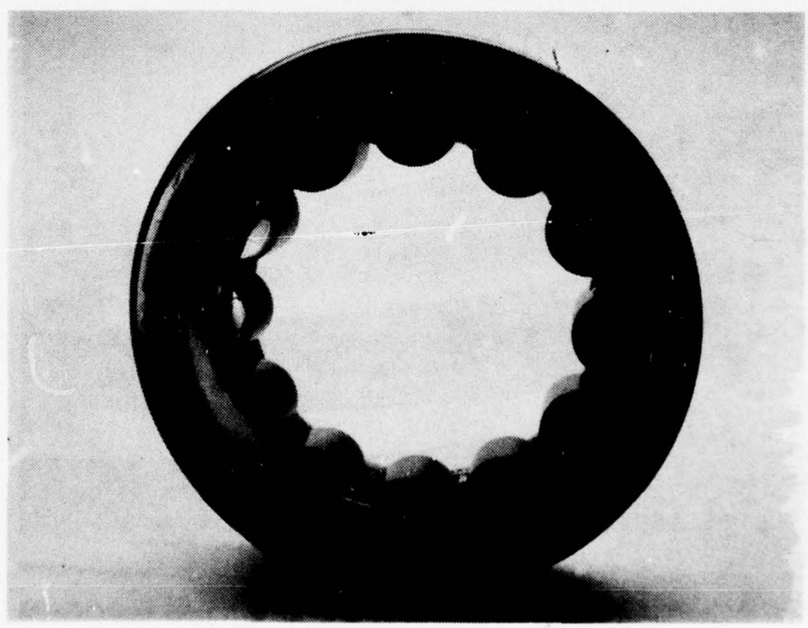

Figure 48. Main input pinion roller bearing after 21-minute loss-of-lube retest of transmission number 1.

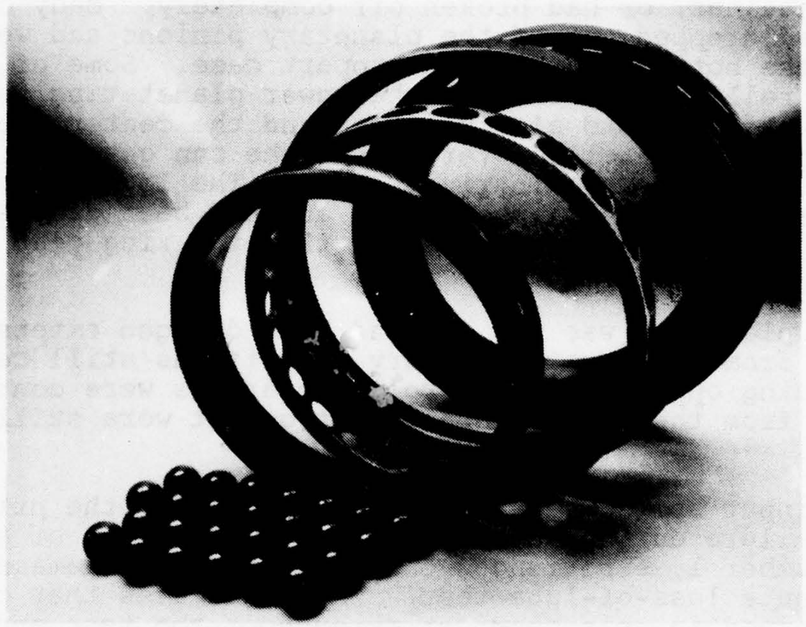

Figure 49. Main gearshaft duplex bearing after 21-minute loss-of-lube retest of transmission number 1.

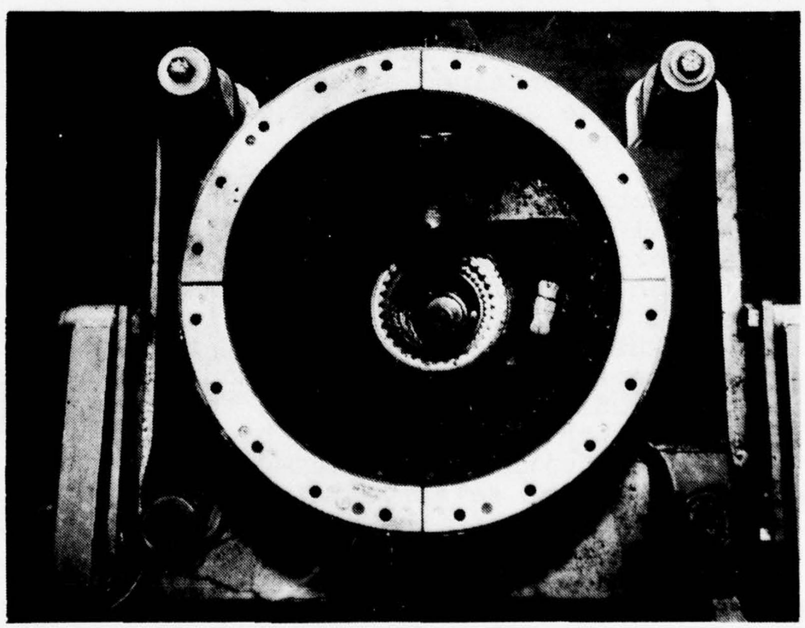

Figure 50. View looking into main and support cases after 21-minute loss-of-lube retest of transmission number 1.

of each retainer, or had broken off completely. Many of the rollers had dropped out of the planetary pinions and were lying at the bottom of the main support case. Some of the planetary rollers went through the lower planet-ring gear mesh. The lower sun gear had also softened and the center portion of its teeth had been rolled over. Both the sun gear and the planetary pinions are carburized gears. The lower ring, which is nitrided, had some chipped teeth and had been damaged by debris, but there was no indication that the ring gear teeth had softened.

The upper planetary was dry and had been damaged extensively by debris from the lower planetary, but it was still capable of continuing operation. The roller bearings were contaminated by debris from the lower planetary stage but were still functional.

The main input spiral bevel gear set, which was the primary mode of failure during the first loss-of-lube test of transmission number 1, experienced only minor scoring damage during the 21-minute loss-of-lube test. This indicates that clearance was maintained in this gear set throughout the test and that a minimum of .012-inch backlash in this set is adequate to provide the required loss-of-lube performance under these test conditions. The triplex ball bearing and the roller bearing which support the main input pinion appeared to have suffered only minor debris damage. The duplex ball bearing which supports the main gear shaft and is located directly below the lower planetary stage contained a substantial amount of debris particles but otherwise appeared to have been unaffected by the high-temperature operation.

The temperature plots of Figures 31 through 33 indicate that the upper mast ball bearing, lower mast roller bearing, and all of the tail rotor drive bearings remained relatively cool during loss-of-lube operation. The lower mast roller bearing was the hottest of these bearings with an outer race temperature of 310°F at the time of the planetary failure. The transmission number 1 configuration utilized modified bearings for these areas. The modified bearings were the same as the standard bearings except that the standard bronze or nylatron retainers were replaced with silver-plated steel retainers (reference Table 1). The relatively low temperatures recorded for these areas indicate that the standard AH-1S bearings would be adequate in these areas during loss-of-lube operation.

6.4 DISCUSSION OF RESULTS OF RETEST OF TRANSMISSION NUMBER 1

It appears that the modifications implemented in the main input area for the retest of transmission number 1 were successful in achieving a 30-minute loss-of-lube capability for this area. The conditions of the gears and bearings in this area after 21 minutes of loss-of-lube operation indicated that they would have operated for the required 30 minutes if a planetary failure had not occurred.

The only remaining survivability problem area is the lower planetary stage. It was anticipated that the relatively small amount of backlash in the planetary gear meshes might prevent attainment of the 30-minute loss-of-lube goal. The condition of the failed lower planetary stage was such, however, that it was impossible to determine the exact cause of the failure (reference Figures 35 through 37). The 4.0-hour loss-of-lube test of the AH-1G HST (reference USAAMRDL TR-76-8) was terminated when the teeth were stripped from the lower sun gear. The planetary bearings were still functional when the failure occurred. The planetary bearings of transmission number 1 were modified in the same manner as the AH-1G bearings. Therefore, at this point in the AH-1S HST test program, it was surmised that the lower planetary stage failure which occurred after 21 minutes of loss-of-lube operation was due to loss of planetary gear mesh clearance. It was recommended that the transmission number 2 configuration be identical to the transmission number 1 retest configuration except that the transmission number 2 planetary pinions be modified to provide additional gear mesh clearance.

7. AH-1S HST TEST OF TRANSMISSION NUMBER 2

7.1 GENERAL OBJECTIVES

The general objective of the test of transmission number 2 was to determine the response of the transmission to the following conditions:

- Total loss of the oil cooler

- Complete loss of the oil supply

7.2 TEST OF TRANSMISSION NUMBER 2

7.2.1 Transmission Number 2 Configuration

As defined in Tables 1 and 6, the configuration for transmission number 2 was the same as the retest of transmission number 1 configuration except that transmission number 2 utilized modified planetary pinions to provide additional planetary gear mesh clearances. The possibility of using a standard AH-1S upper mast ball bearing, lower mast roller bearing and standard tail rotor drive bearings was considered since the previous testing had indicated that the modified bearings were not required in these locations. However, since the modified bearings had already been procured for this test and since procurement of standard bearings for these locations would have resulted in additional cost and a possible delay, it was decided that the modified bearings would be used.

Thermocouple locations for this test were identical to those of the retest of transmission number 1 as defined in Table 2 and Figure 2. An oil cooler bypass system and an oil drainage system was installed (reference Figure 3).

7.2.2 Description of Tests of Transmission Number 2

Transmission number 2 was green run according to the load and speed schedule of Table 3 in order to meet the following objectives:

- To verify proper assembly and to give all new parts a break-in period.

- To check out all instrumentation.

Following the green run, thermal tests were performed according to Table 7 to determine the response of the transmission to total loss of the oil cooler during operation at 950 hp and at 1134 hp.

TABLE 7. THERMAL BASELINE TESTING LOAD AND SPEED SCHEDULE, TRANSMISSION NUMBER 2

Step No.	Run Time (hr)	Oil Cooler Bypassed	XMSN Input (rpm)	XMSN Input (hp) [a]	Main Rotor Mast Torque (in.-lb)	Main Rotor Mast Lift (lb)	Main Rotor Mast Shear (lb)	Tail Rotor (hp)	Oil-In Temp [b] (^{o}F)
1	c	no	6600	950	176,042	7200	575	30	230
2	d	yes	6600	950	176,042	7200	575	30	-
3	c	no	6600	1134	205,415	7200	575	30	230
4	d	yes	6600	1134	205,415	7200	575	30	-

a. This value includes 1.6% of the transmitted main rotor and tail rotor horsepower.

b. These are stabilized temperatures; stabilized is defined as $1^{o}F$ or less change in 0.1 hour.

c. Run until the specified temperature is attained.

d. Run until the oil temperature stabilizes or until the temperature of the hottest monitored component reaches $400^{o}F$.

The loss-of-lubrication test was conducted according to Table 8 to determine the response of the transmission to loss of the bypass valve and/or loss of the lower part of the sump, which would result in the loss of the oil supply.

7.3 RESULTS OF TESTS OF TRANSMISSION NUMBER 2

7.3.1 Results of Green Run of Transmission Number 2

The green run was completed per the load and speed schedule of Table 3. The post-green run inspection indicated that the transmission was functioning normally. The instrumentation appeared to be working properly.

7.3.2 Results of Thermal Testing of Transmission Number 2

The thermal testing of transmission number 2 was completed per the load and speed schedule of Table 7; however, some problems developed during the performance of these tests. One problem was that a significant quantity of oil was leaking from the main input area of the transmission. Although it was difficult to positively ascertain the source of the leak, it appeared to be coming from the hole in the 204-040-629-5 retainer assembly which provided passage for the thermocouple wires that monitored the temperatures of the input pinion tooth root and the input triplex bearing inner rings. The same problem had occurred during the test of transmission number 1 but efforts to stop that leak were successful. Unfortunately, the oil leaked continuously during the thermal testing of transmission number 2 and near the completion of each of the two oil cooler bypass tests (one at 950 hp and the other at 1134 hp) the oil pressure dropped from 55 psi to a fluctuating value between 40 and 45 psi. Another problem which hampered the thermal testing of transmission number 2 was that the thermocouple monitoring the oil-inlet temperature was apparently not functioning properly. If the oil temperature stabilizes when the transmission is operating with the oil cooler fully bypassed, then the oil-inlet temperature and the oil-outlet temperatures should be the same. This fact is verified by the two oil cooler bypass tests of transmission number 1 (reference Figures 6 and 7). However, at stabilization temperatures for the two oil cooler bypass tests the oil-inlet temperatures were 22°F and 90°F cooler than the oil-outlet temperatures for the 950 hp and the 1134 hp runs respectively. Comparing the temperatures at stabilization for the two runs of transmission number 2 (shown in Figures 51 and 52) with the two runs of transmission number 1 (Figures 6 and 7) leads one to conclude that the oil-outlet temperature of transmission number 2 was probably accurate and the oil-inlet temperature was most likely erroneous. No conclusions will be drawn from the data collected during these two tests since their validity is questionable.

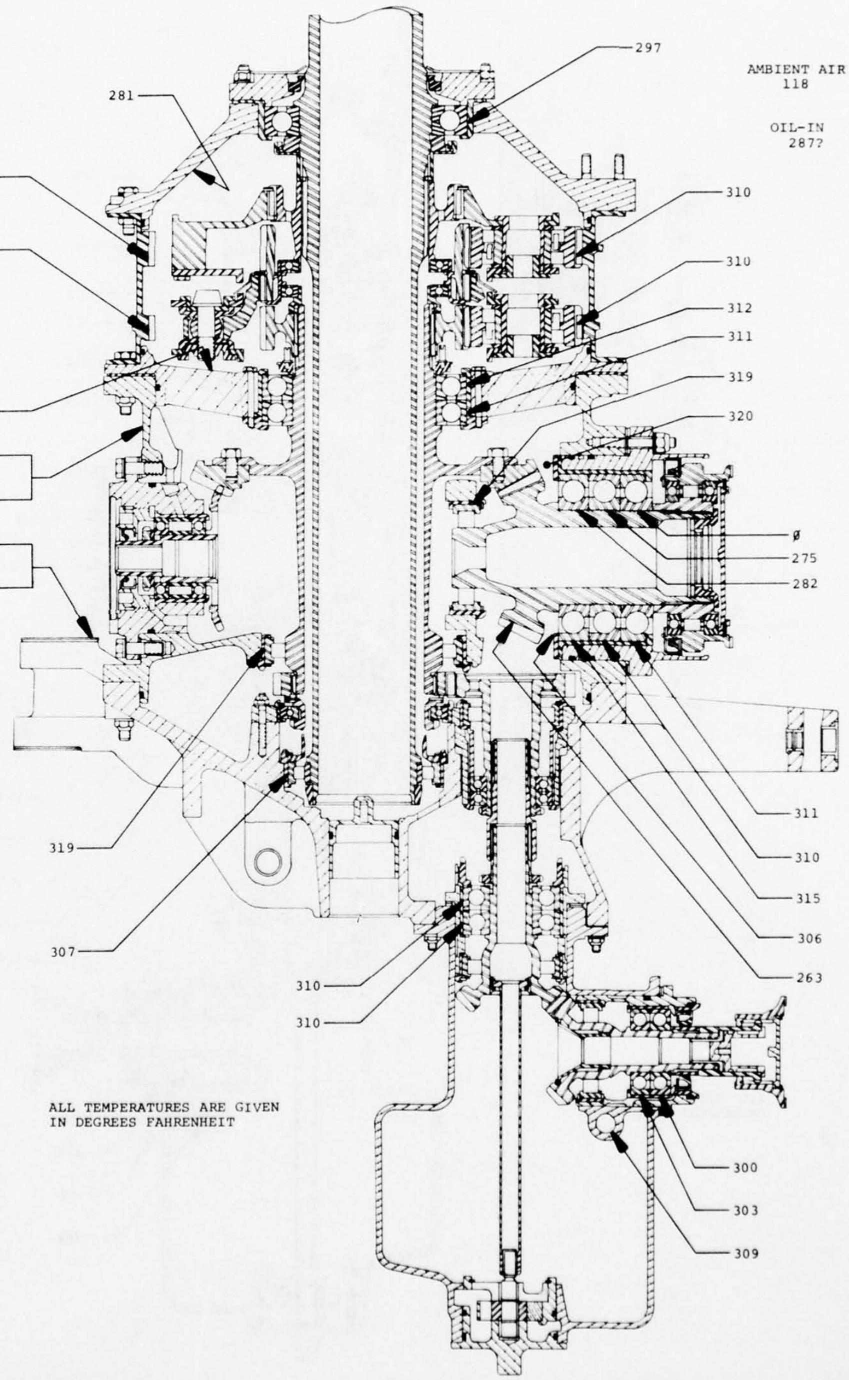

Figure 51. Transmission number 2 temperatures at 950 hp with the oil cooler bypassed but with the oil level about 4 quarts low.

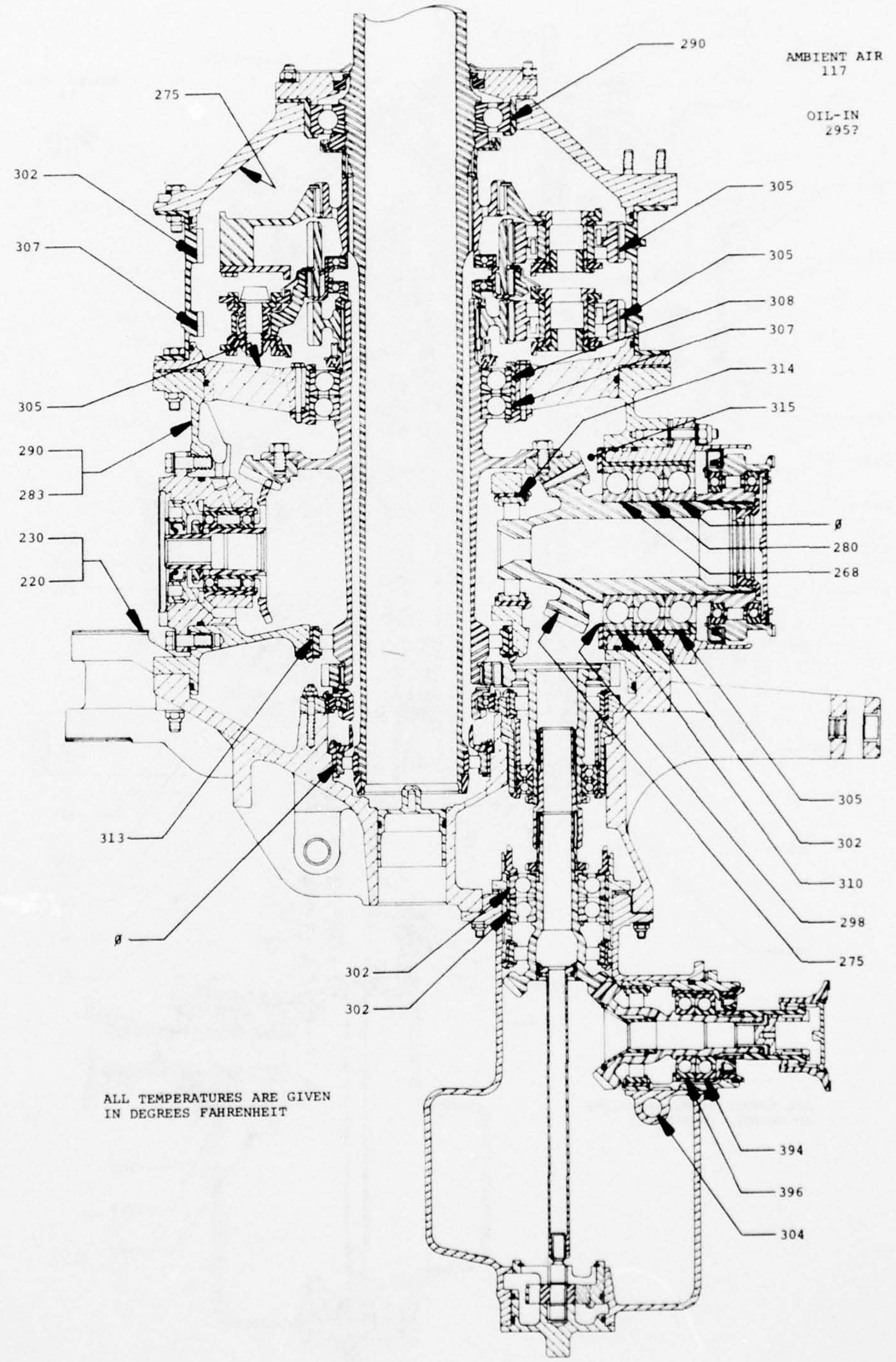

Figure 52. Transmission number 2 temperatures at 1134 hp with the oil cooler bypassed but with the oil level about 5 quarts low.

7.3.3 Results of Loss-of-Lube Test of Transmission Number 2

The loss-of-lube test of transmission number 2 was performed according to the load and speed schedule of Table 8. The test transmission was operated at 950 hp (84 percent of MCP) under normal lubrication conditions until the inlet oil temperature stabilized at 230°F. Then, with the transmission still operating at 950 hp (30 hp through the tail rotor, lift and bending loads applied to the main rotor mast), valve C was opened and valves A and B were closed (reference Figure 3) allowing the oil to be pumped from the transmission. After complete loss of the oil supply, the transmission continued to operate for 19 minutes before torque was lost due to a failure of the lower planetary stage. Figure 53 is a plot of the lower planetary ring gear temperatures recorded during the loss-of-lube test. At failure, the ring gear temperature was in excess of 950°F just as it was for the retest of transmission number 1. Figures 54 through 65 show temperature plots of various components during the 19-minute loss-of-lube test and Figure 66 shows transmission temperatures at failure.

Disassembly of the transmission following the 19-minute loss-of-lube test revealed that this failure was very similar to the one which occurred after the 21-minute loss-of-lube retest of transmission number 1. Figures 67 through 82 show various components following the loss-of-lube test of transmission number 2. The teeth had been stripped from all four of the lower planetary pinions. One of the lower planetary pinions was oblong and deformed. Some of the rollers retained within this pinion were skewed sideways. The tangs which retain these rollers had broken off of the bearing cage. The other three lower planetary pinions still appeared round. The rollers were not skewed and were retained properly. The lower planetary sun gear teeth had softened and the center portion of the teeth had been rolled over in a manner similar to the sun gear of the 21-minute loss-of-lube test of transmission number 1. The upper and lower ring gears were covered with a carbon residue but the teeth had not softened like the lower planetary pinions or the lower ring gear.

The upper planetary assembly was dry when disassembled but it was still fully functional. There was no evidence that gear clearances or bearing clearances had been lost. Both the upper and lower planetary support bearings turned roughly when removed from the transmission.

The teeth of the main input spiral bevel gear set were moderately scored after the 19-minute loss-of-lube run. The triplex ball bearing and the roller bearing which support the main input pinion still had slight traces of oil when removed from the transmission. The balls and rollers (which were made of

TABLE 8. LOSS-OF-OIL TEST LOAD AND SPEED SCHEDULE, TRANSMISSION NUMBER 2

Step No.	Run Time (hr)	XMSN Input (rpm)	XMSN Input a (hp)	Main Rotor Mast Torque (in.-lb)	Main Rotor Mast Lift (lb)	Main Rotor Mast Shear (lb)	Tail Rotor (hp)	Oil-In Temp b (°F)
1	c	6600	950	176,042	7200	575	30	230
2	.5	6600	950	176,042	7200	575	30	
3	30 sec	6600	950	176,042	7200	575	110	
4	.2	6600	950	176,042	7200	575	30	
5	30 sec	6600	950	176,042	7200	575	110	

\- REPEAT STEPS 4 & 5 UNTIL FAILURE OR UNTIL IMPENDING FAILURE IS OBVIOUS.

a. This value includes 1.6% of the transmitted main rotor and tail rotor horsepower.

b. These are stabilized temperatures; stabilized is defined as 1°F or less change in 0.1 hour.

c. Run until the specified temperature is attained. Then drain the oil by opening valve C and closing valves A & B (ref. Figure 2). This initiates Step 2.

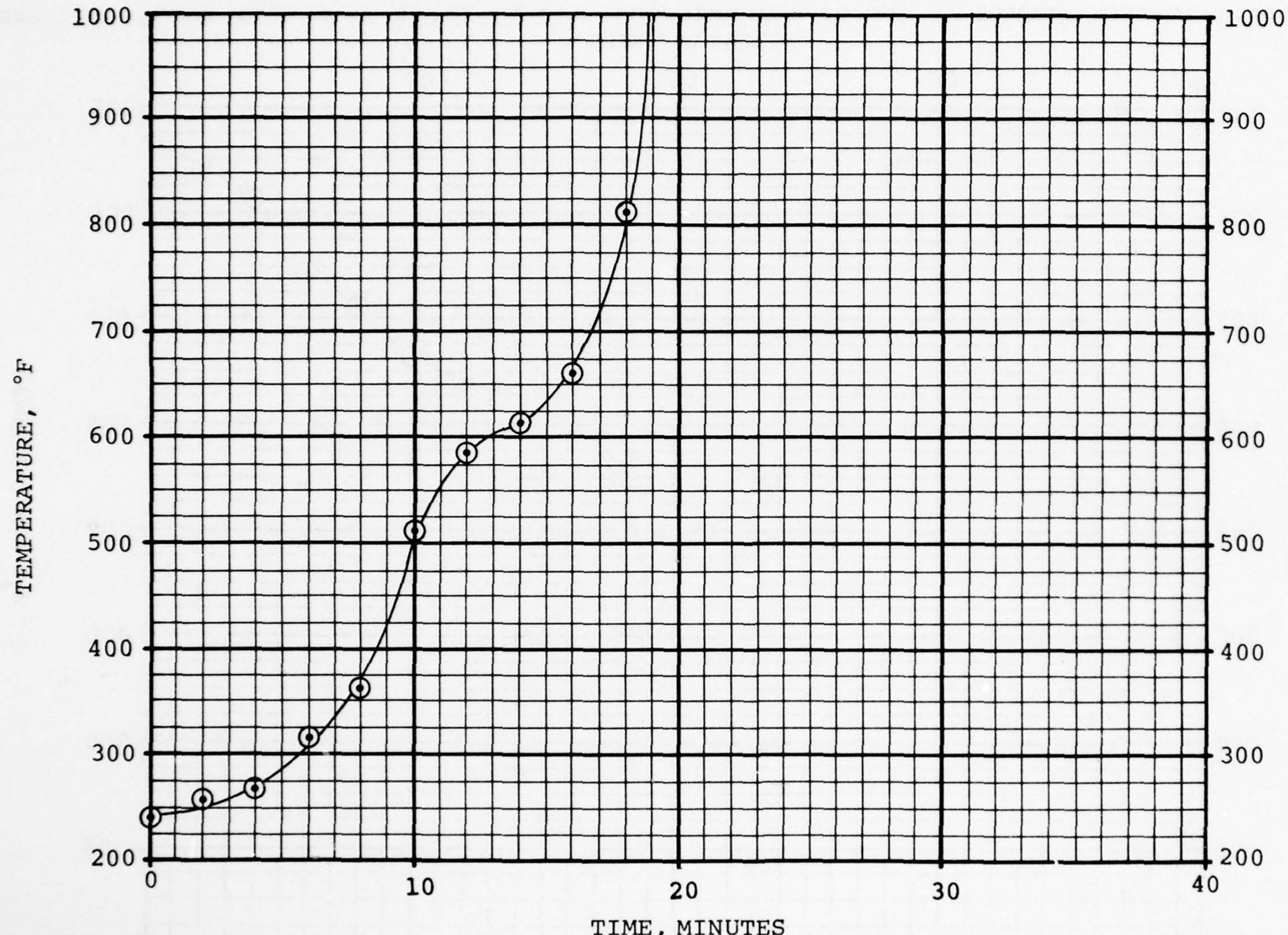

Figure 53. Lower ring gear tooth root temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 13)

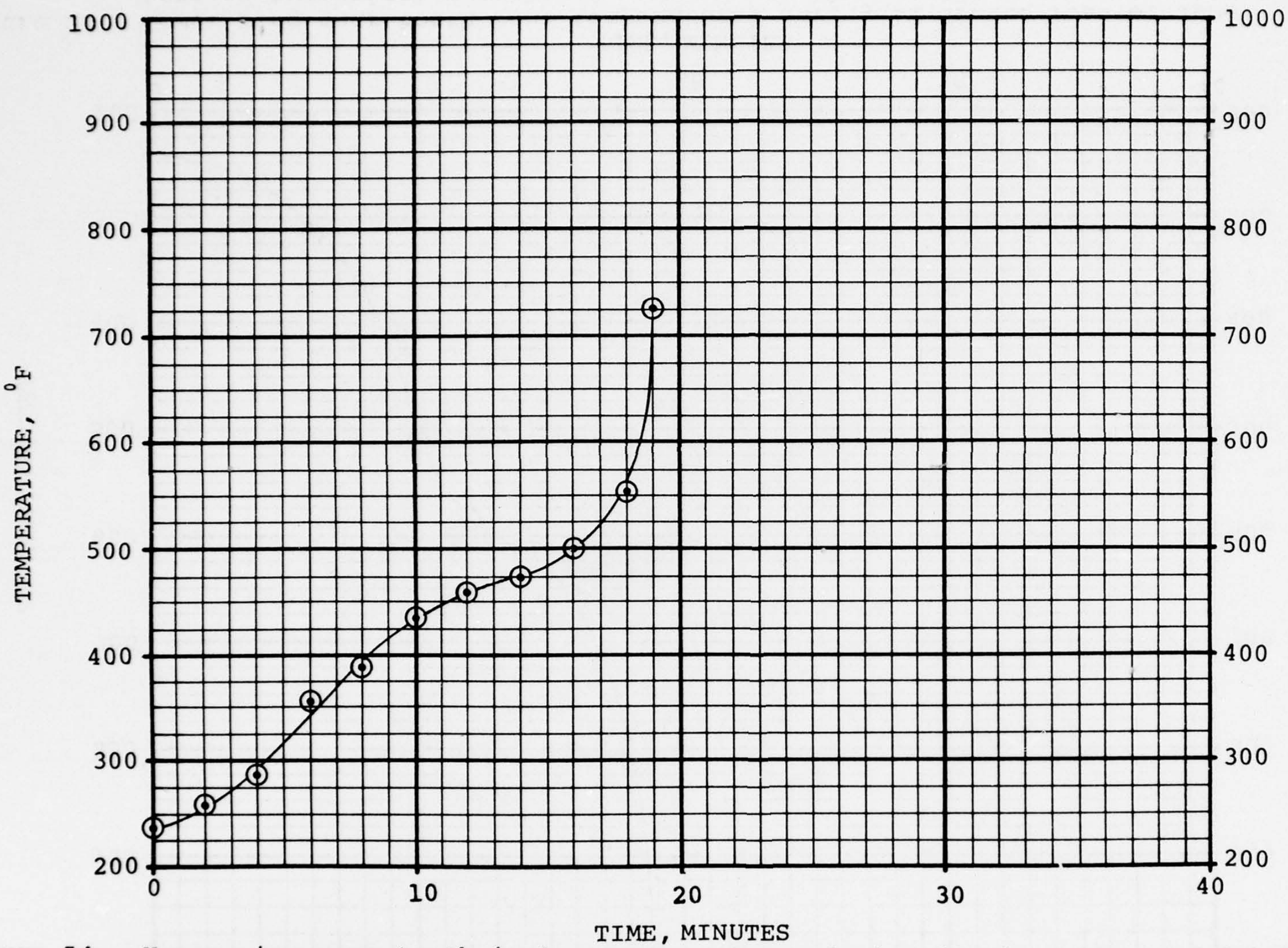

Figure 54. Upper ring gear tooth implant temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 10)

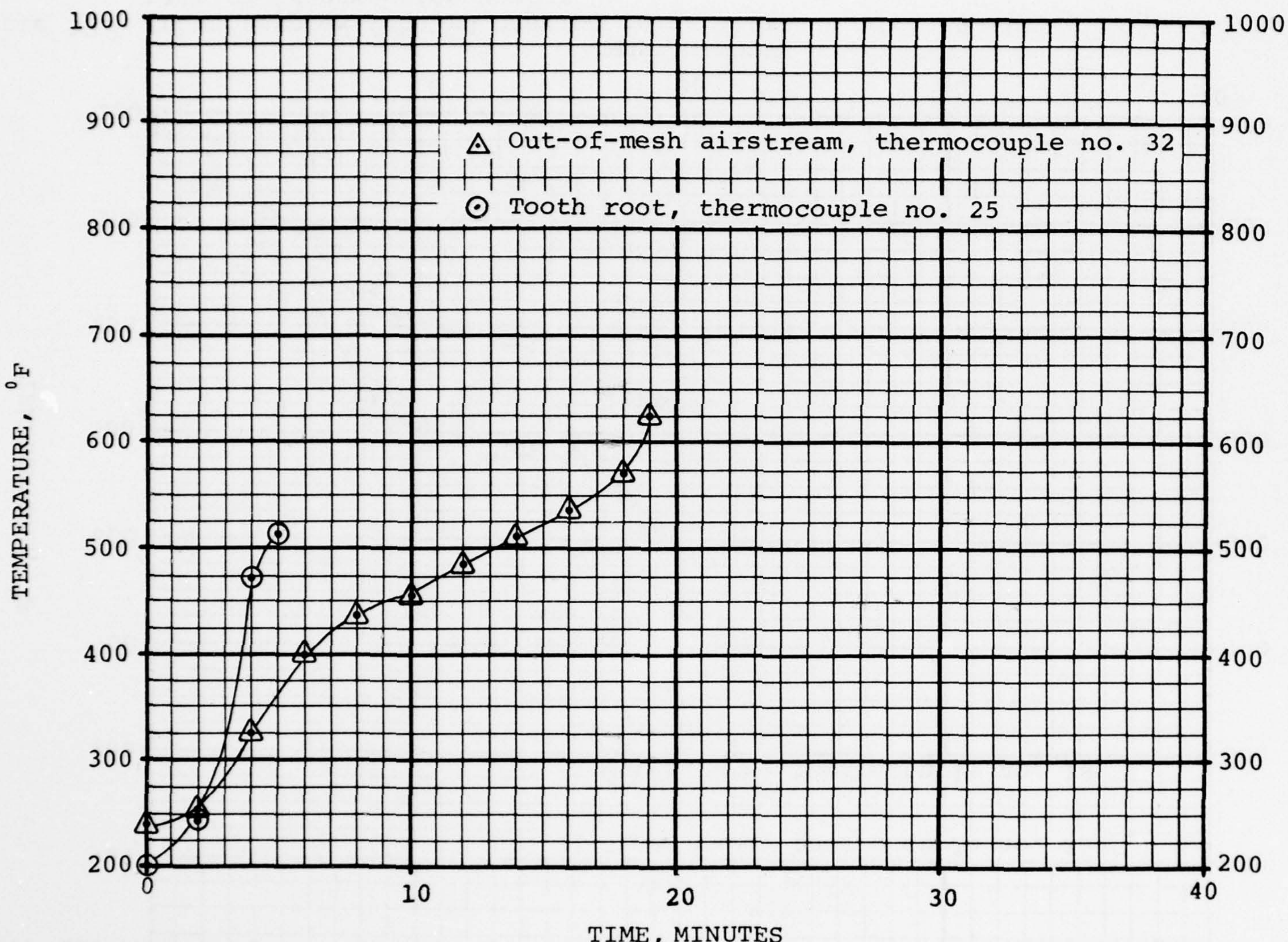

Figure 55. Input pinion temperatures during 19-minute loss-of-lube test of transmission number 2.

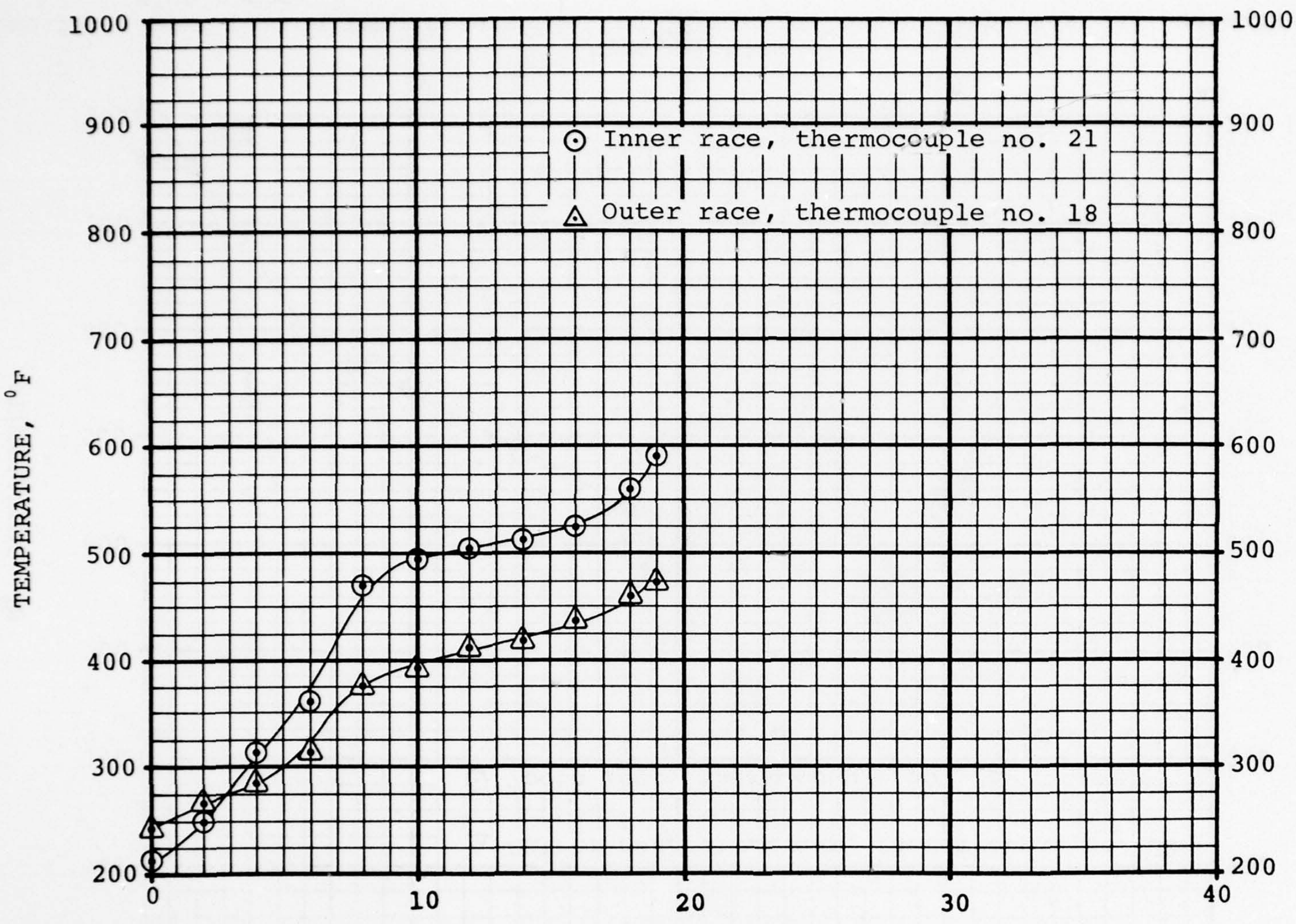

Figure 56. Input triplex inboard bearing temperatures during 19-minute loss-of-lube test of transmission number 2.

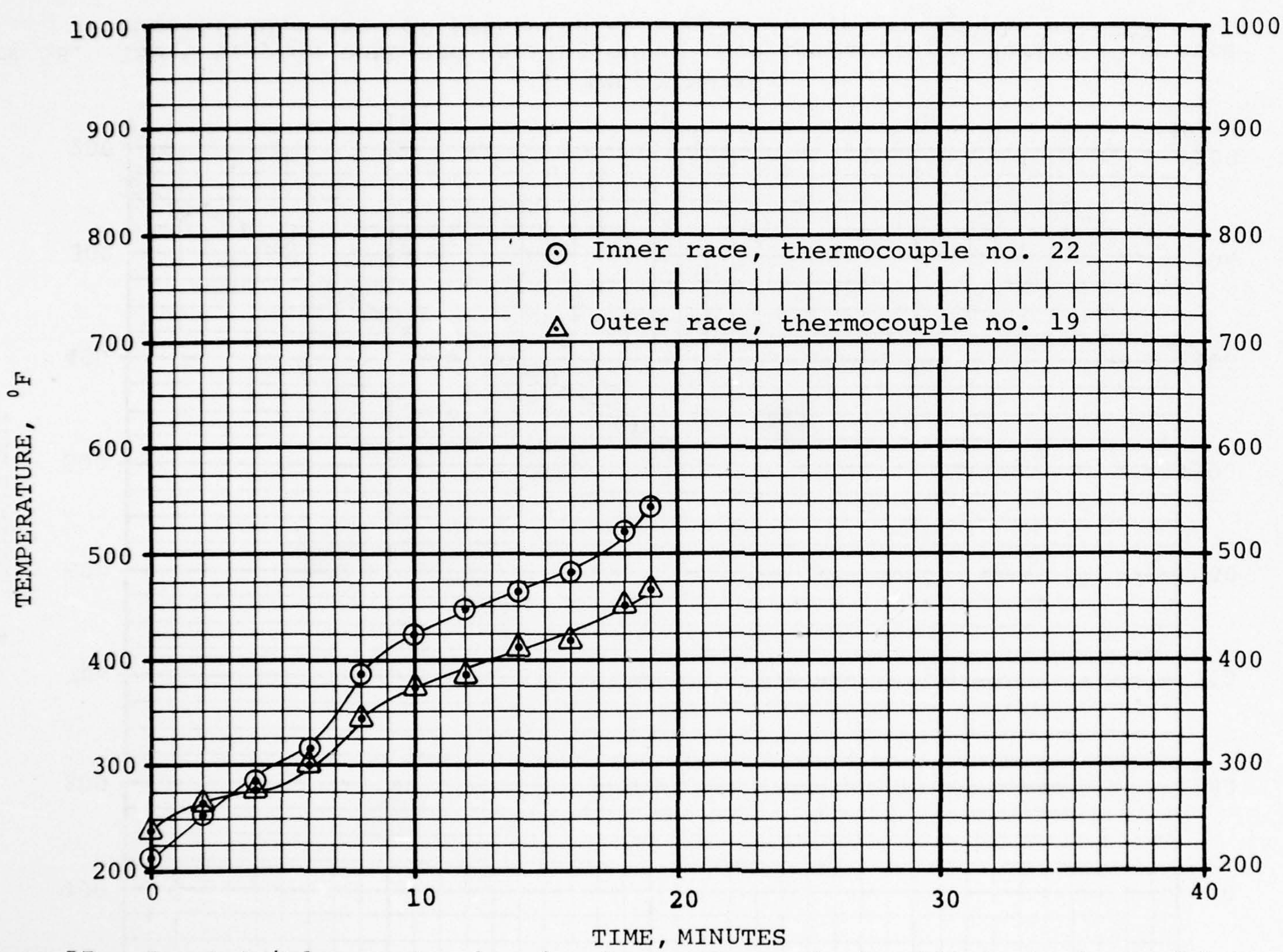

Figure 57. Input triplex center bearing temperatures during 19-minute loss-of-lube test of transmission number 2.

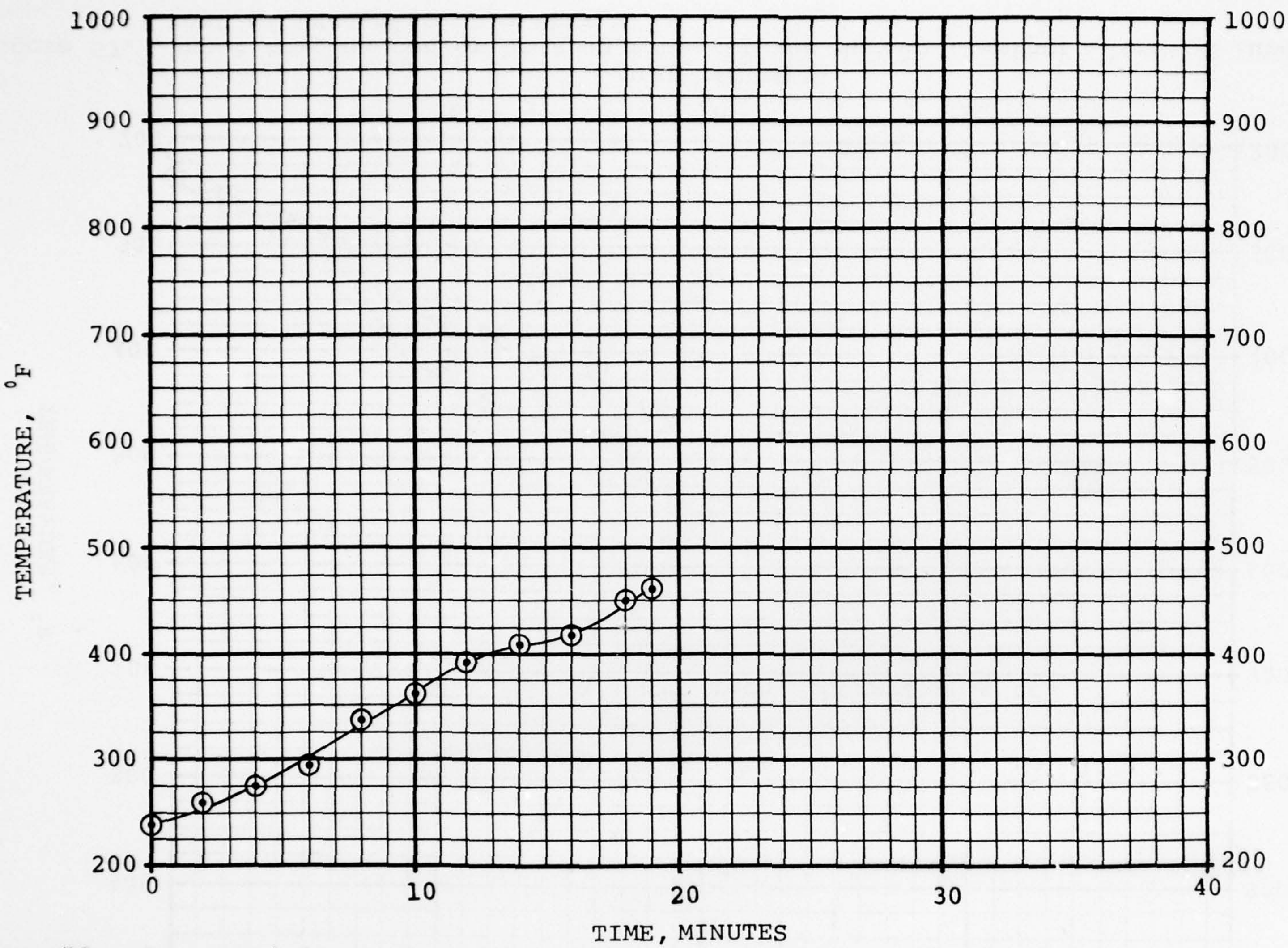

Figure 58. Input triplex outboard bearing outer race temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 20)

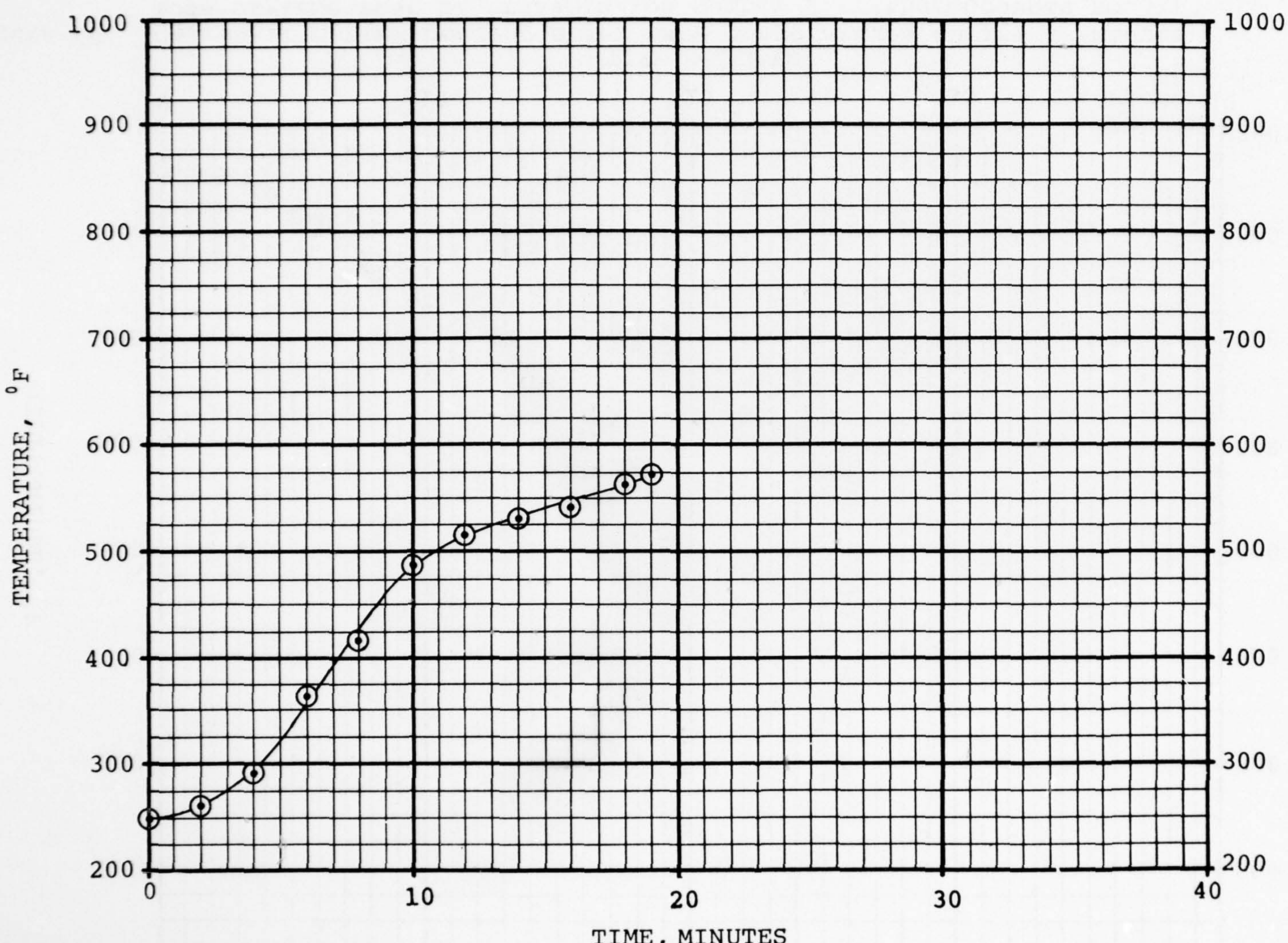

Figure 59. Input pinion roller bearing outer race temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 5)

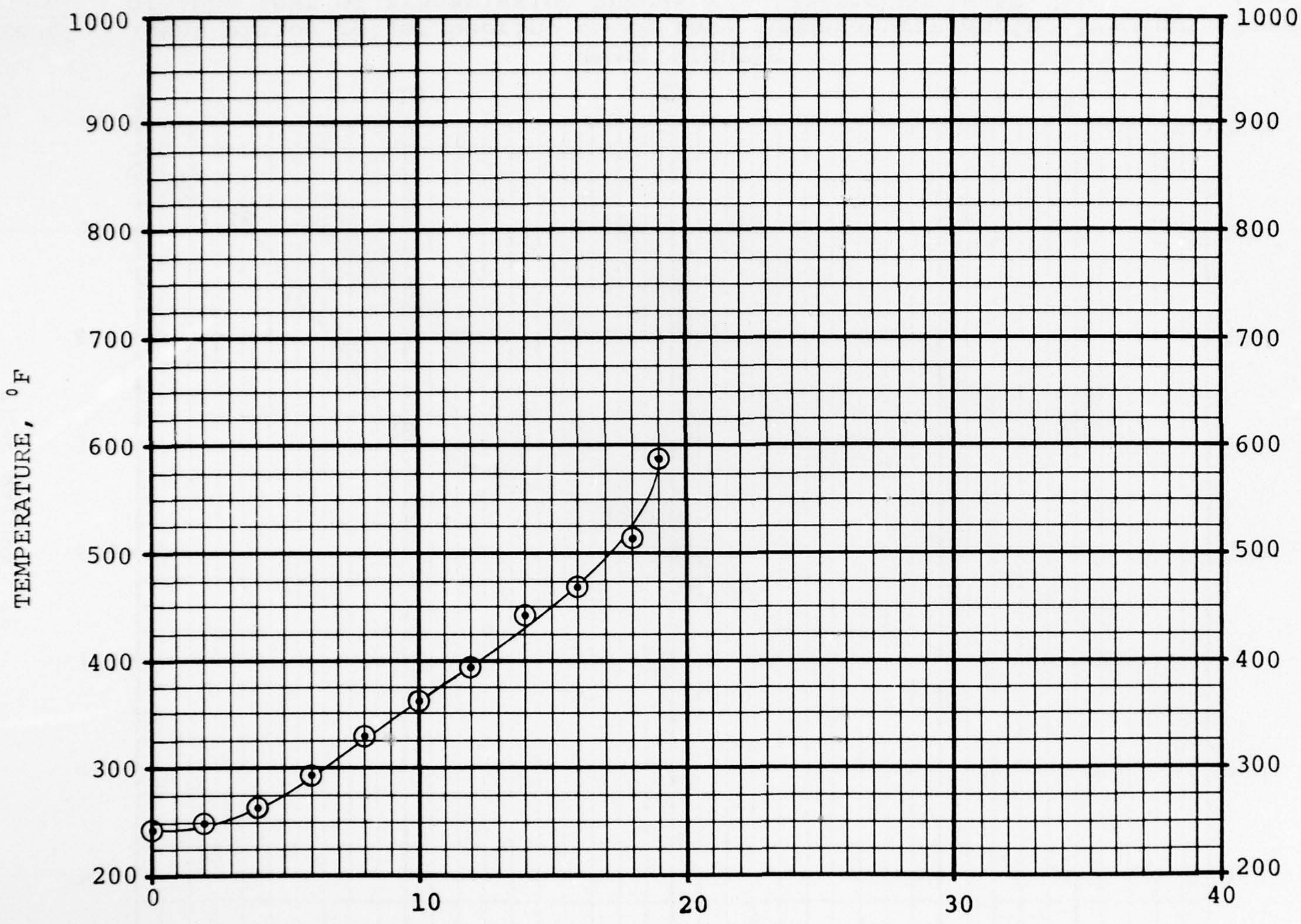

Figure 60. Gearshaft duplex bearing outer race temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 3)

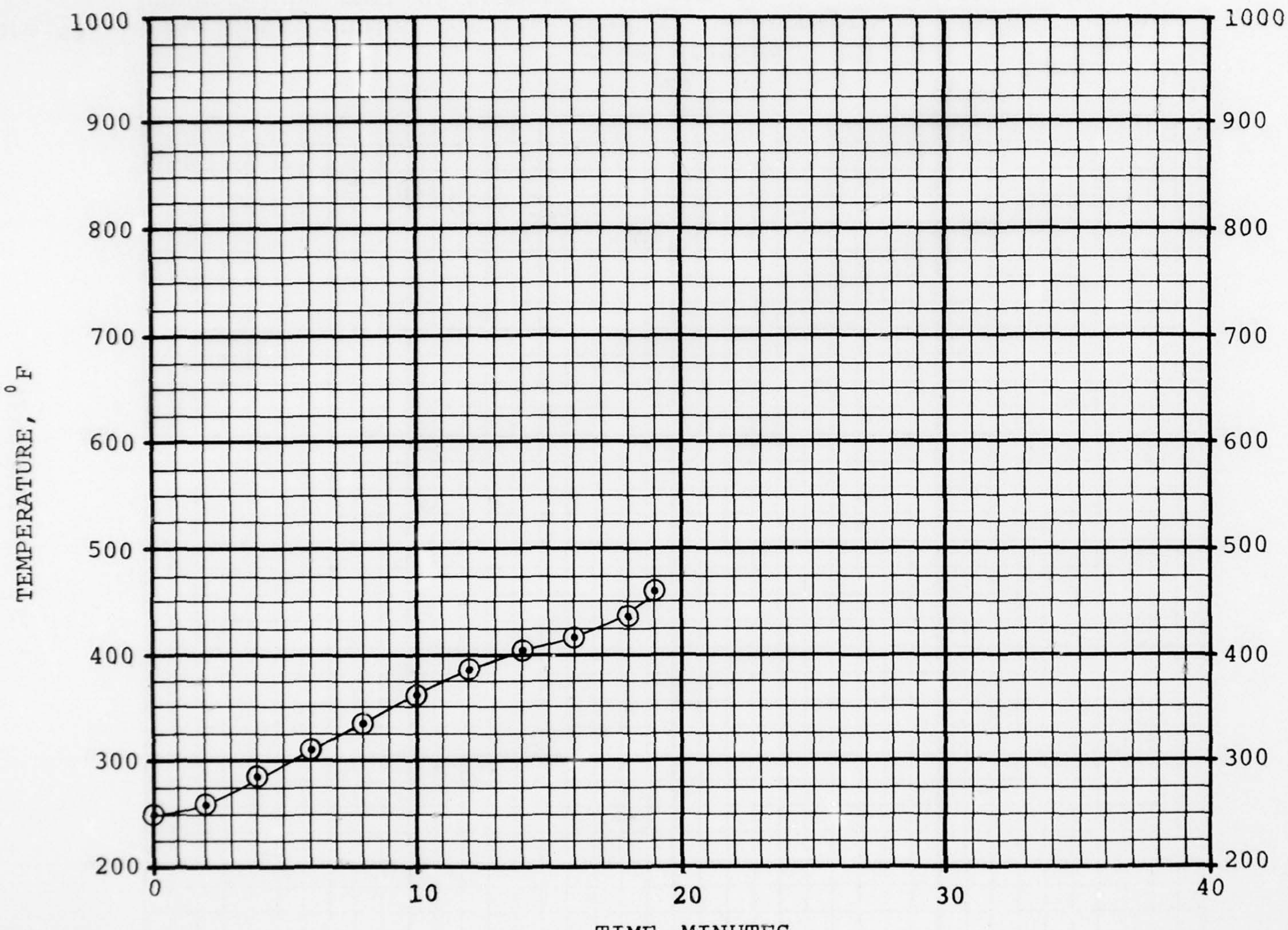

Figure 61. Gearshaft roller bearing outer race temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 6)

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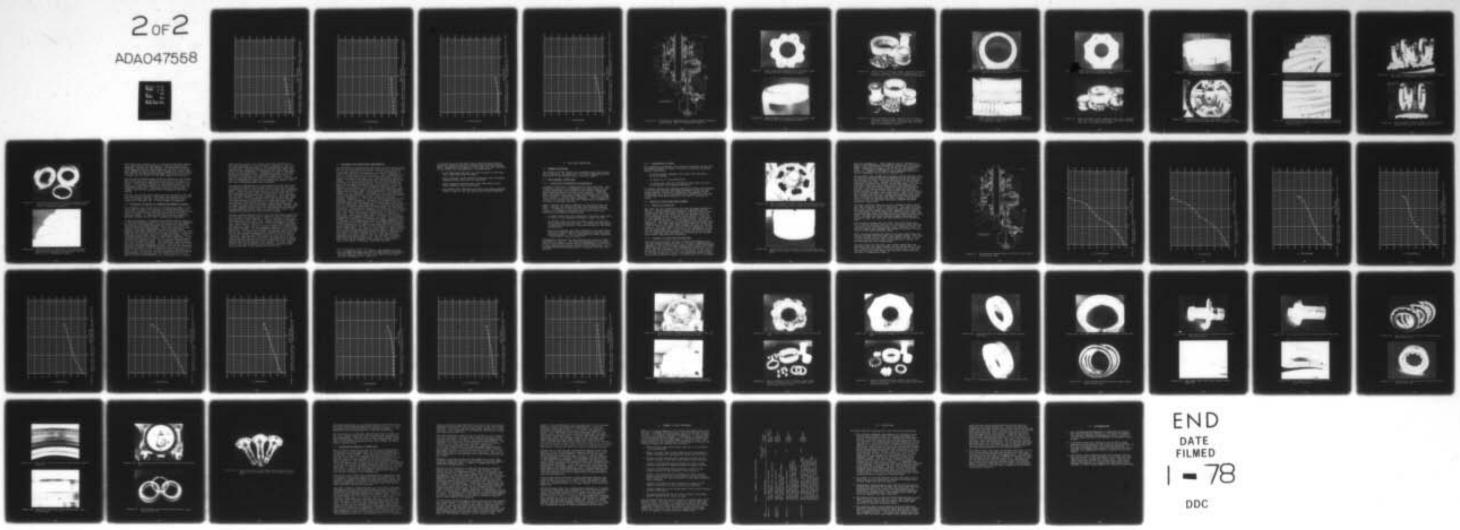

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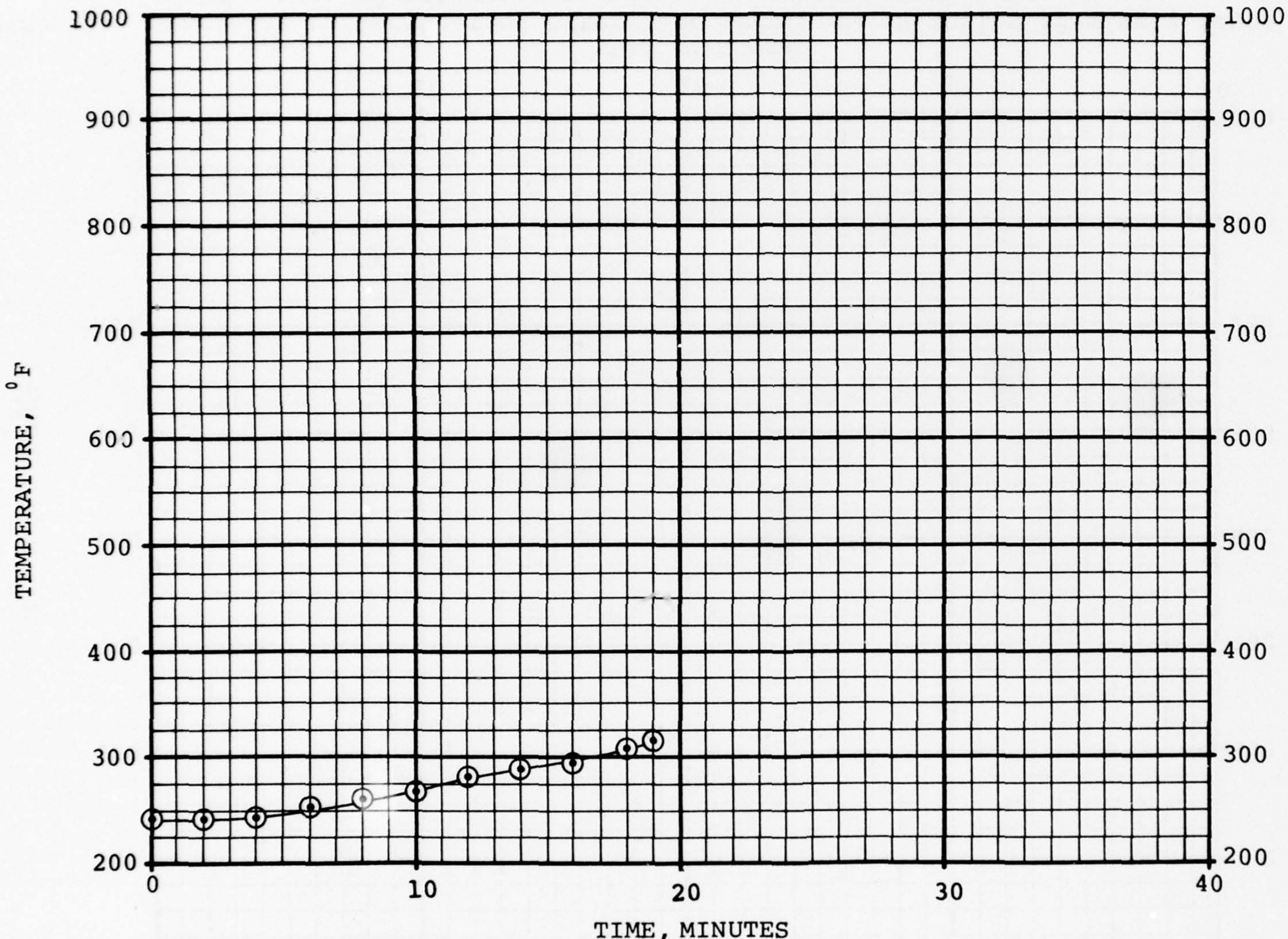


Figure 62. Sump input, duplex bearing outer race temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 14)

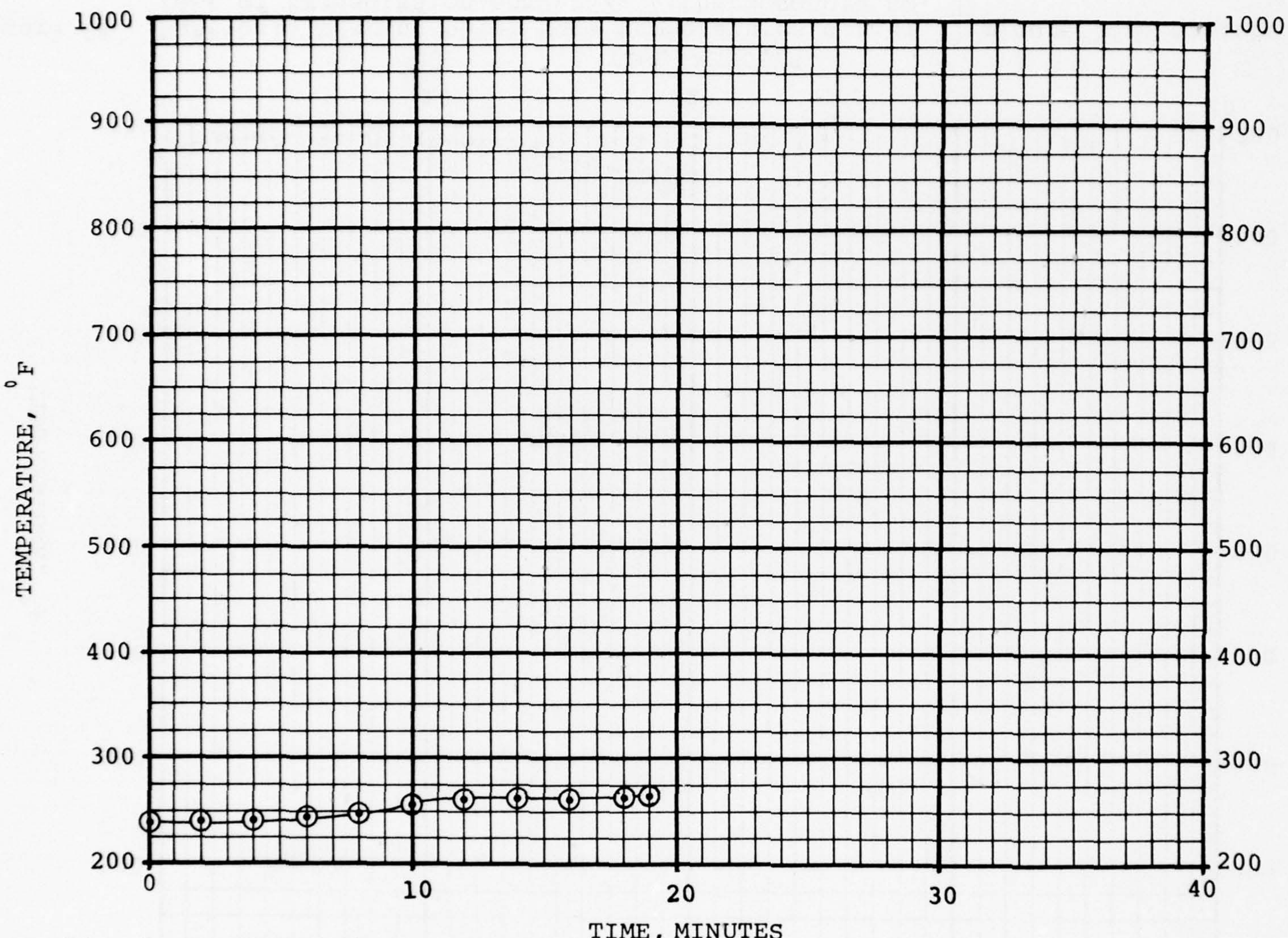


Figure 63. Sump output, duplex bearing outer race temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 16)

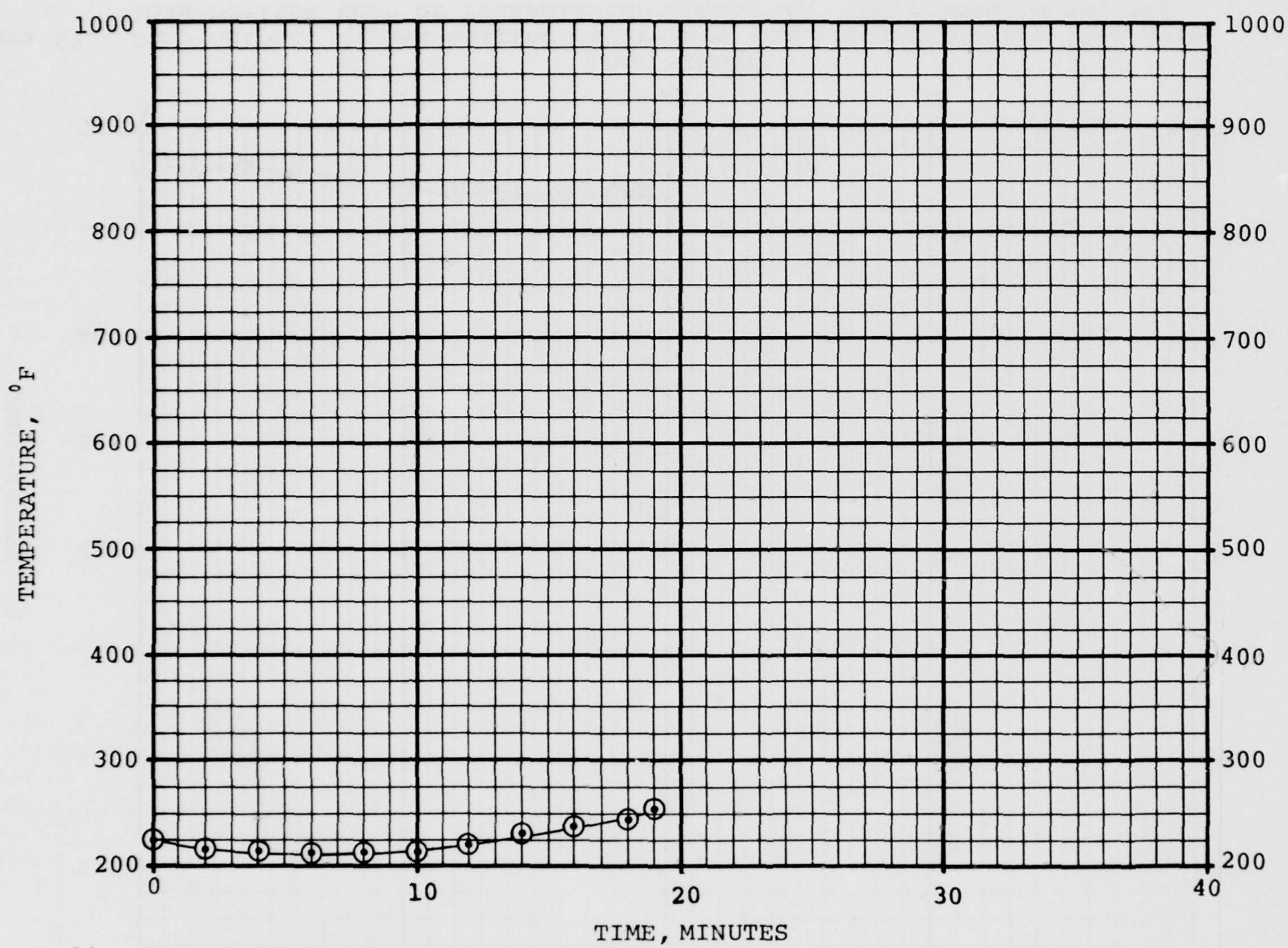


Figure 64. Mast ball bearing outer race temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 31)

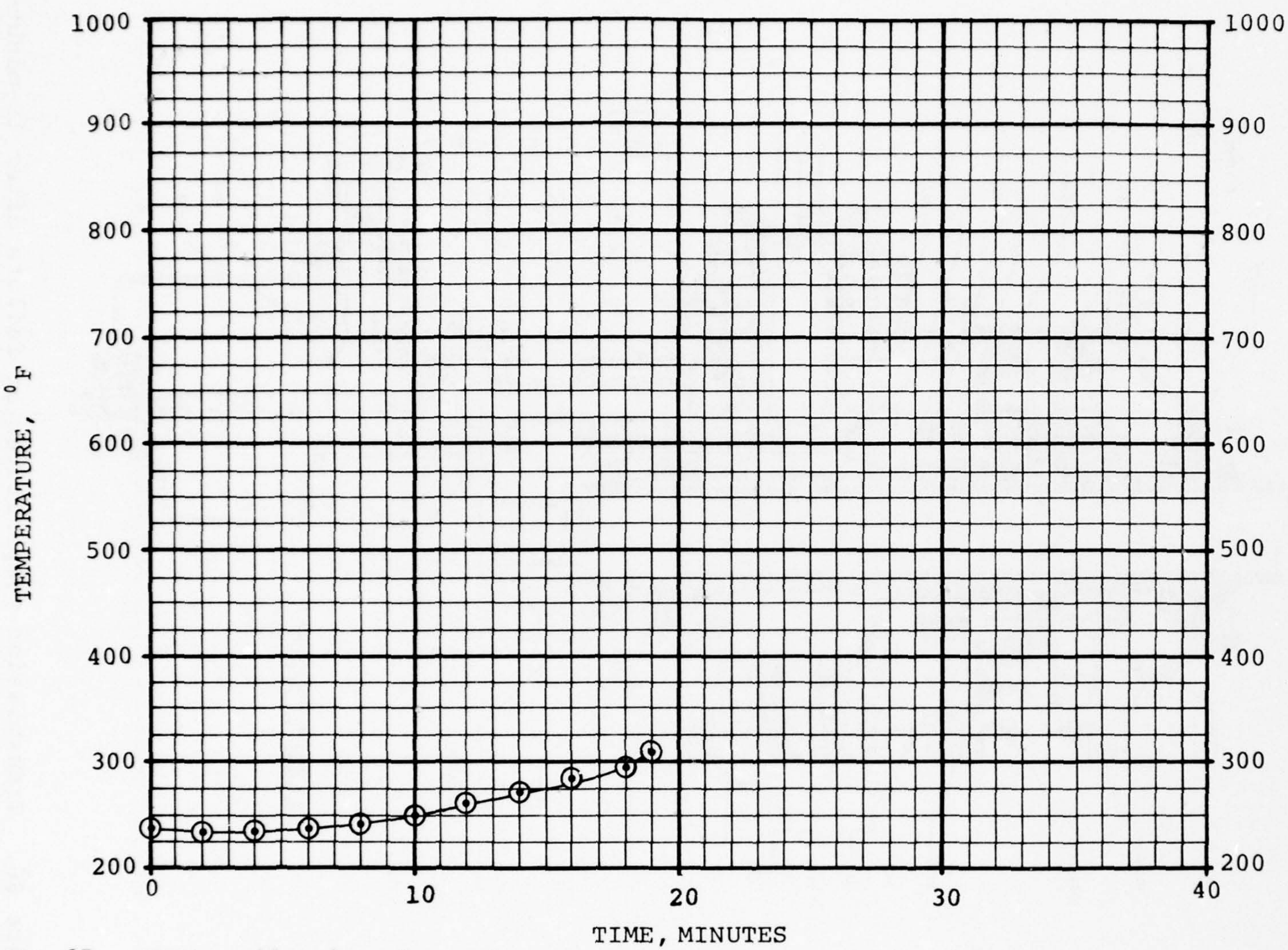


Figure 65. Mast roller bearing outer race temperatures during 19-minute loss-of-lube test of transmission number 2. (thermocouple no. 30)

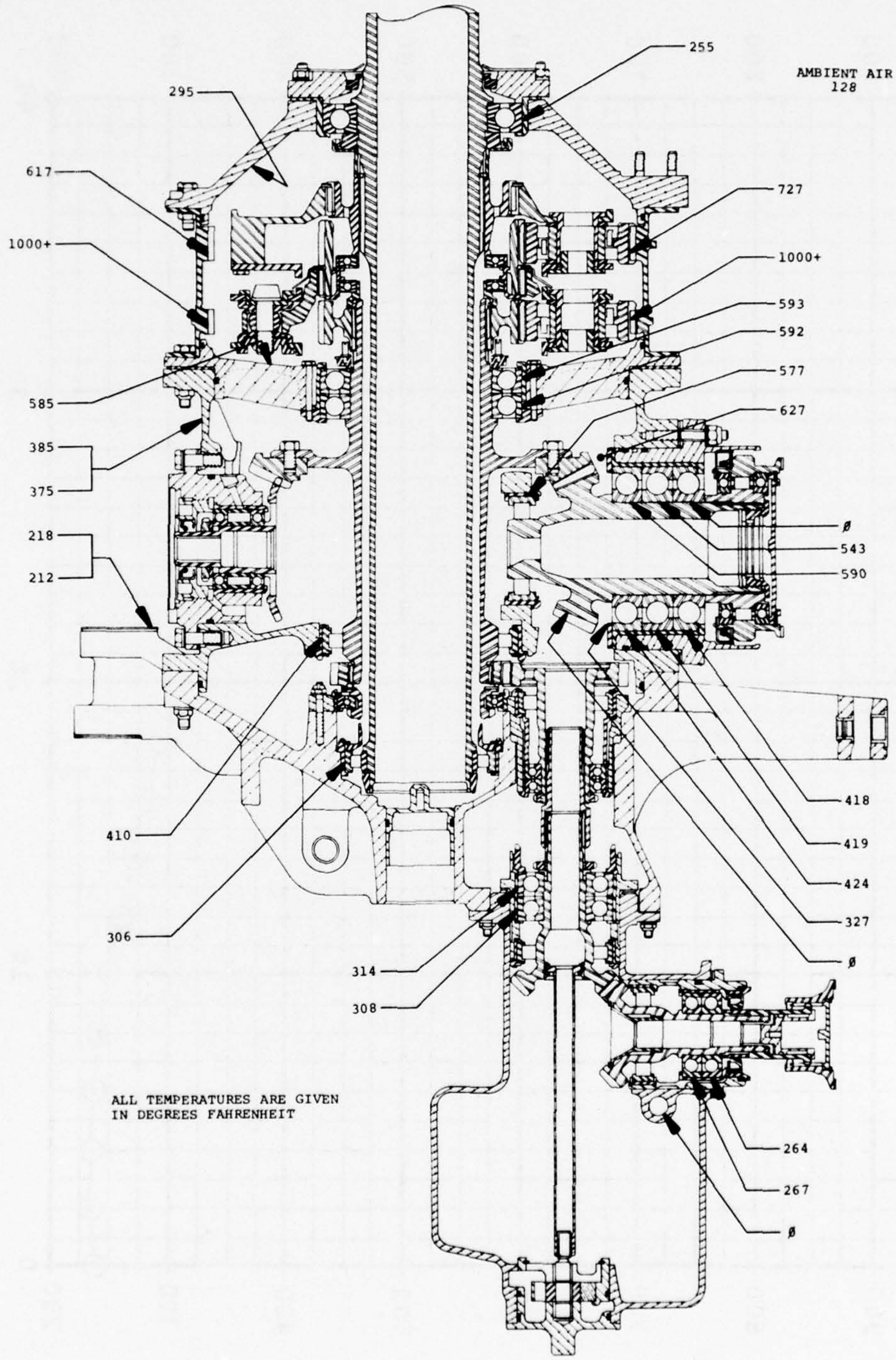


Figure 66. Transmission temperatures at failure after 19-minute loss-of-lube test of transmission number 2.

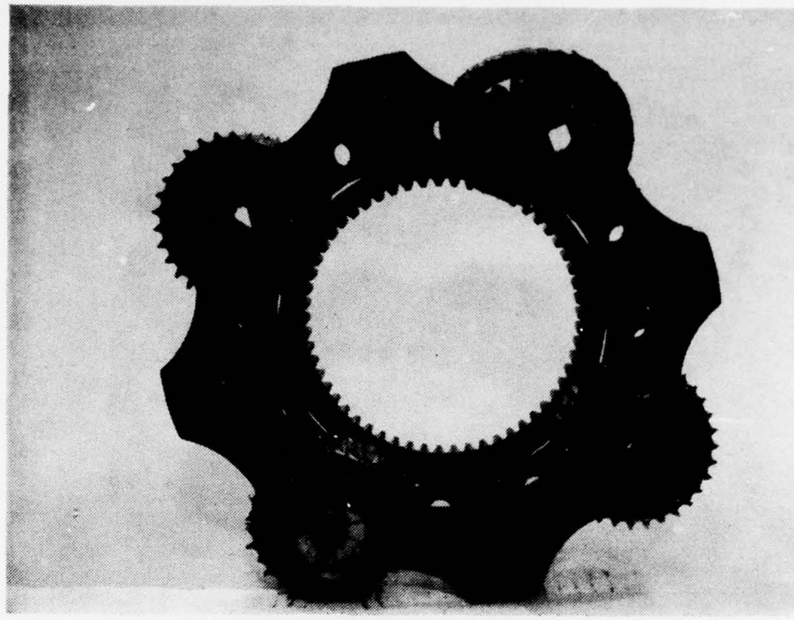


Figure 67. Lower planetary assembly after 19-minute loss-of-lube test of transmission number 2.

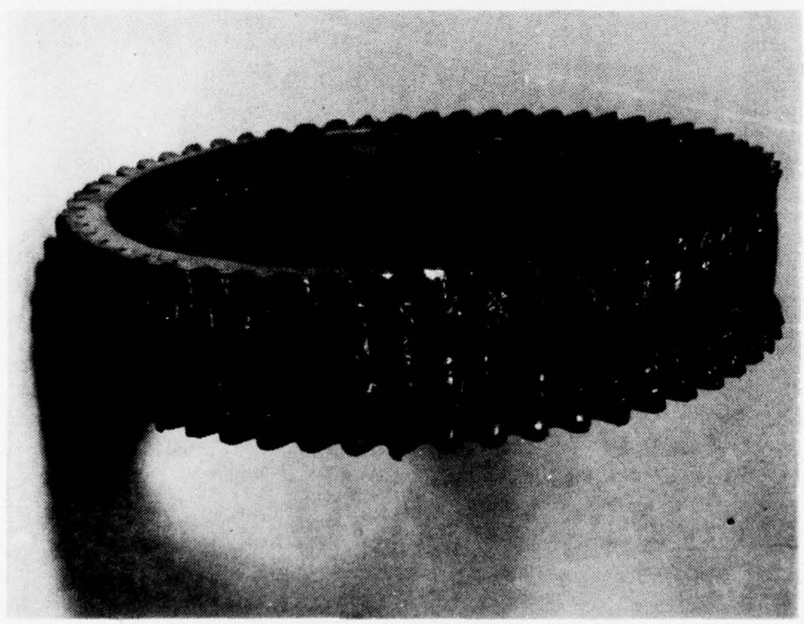


Figure 68. Lower planetary sun gear after 19-minute loss-of-lube test of transmission number 2.

Figure 69. Oblong lower planetary pinion, bearing inner race, rollers, retainer, and roller guides after 19-minute loss-of-lube test of transmission number 2.

Figure 70. Lower planetary pinion (typical of 3 of the 4 pinions), bearing inner race, rollers, retainer, and roller guides after 19-minute loss-of-lube test of transmission number 2.

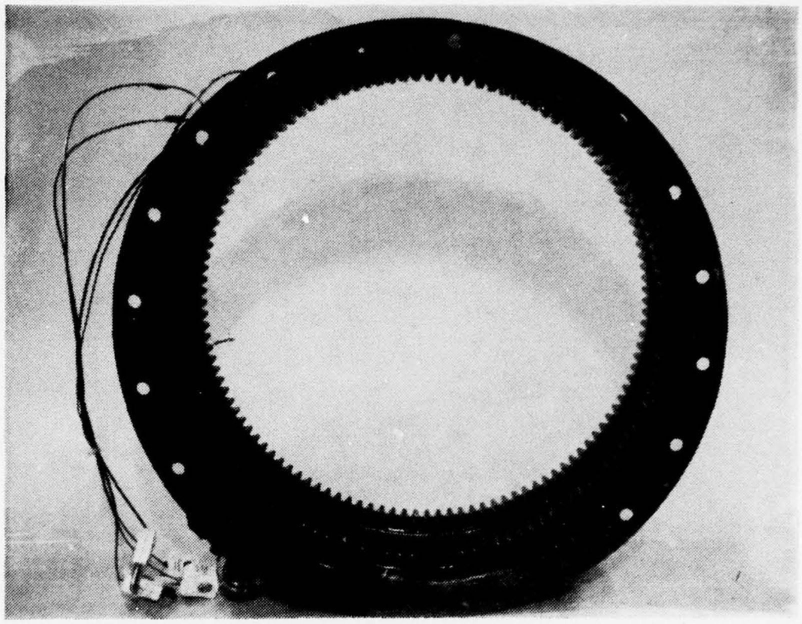


Figure 71. Ring gear case after 19-minute loss-of-lube test of transmission number 2.

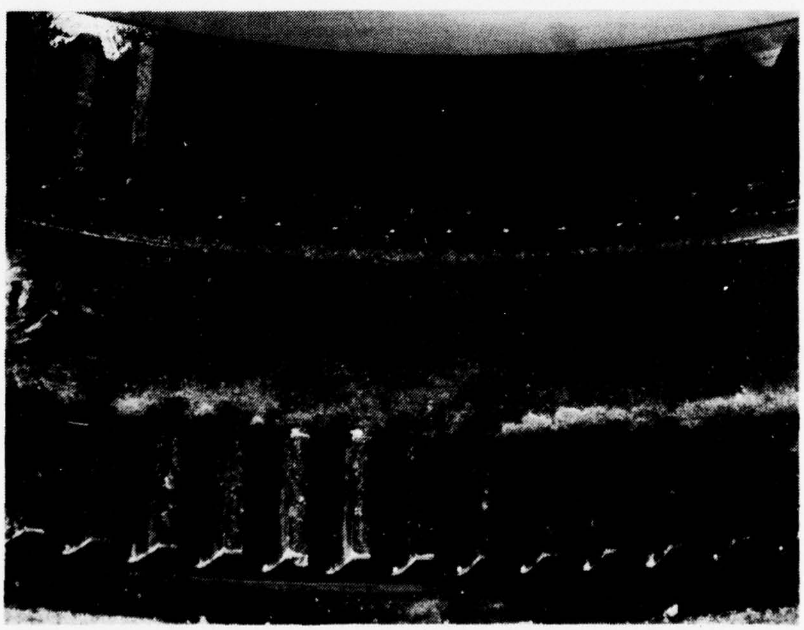
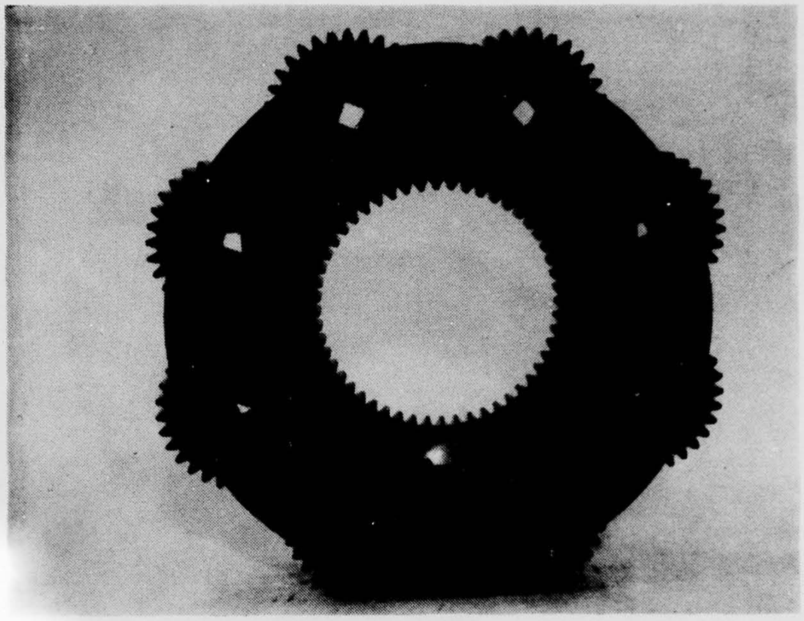


Figure 72. Upper ring gear teeth (top) and lower ring gear teeth (bottom) after 19-minute loss-of-lube test of transmission number 2.



Fi[illegible]. Upper planetary assembly after 19-minute loss-of-lube test of transmission number 2.

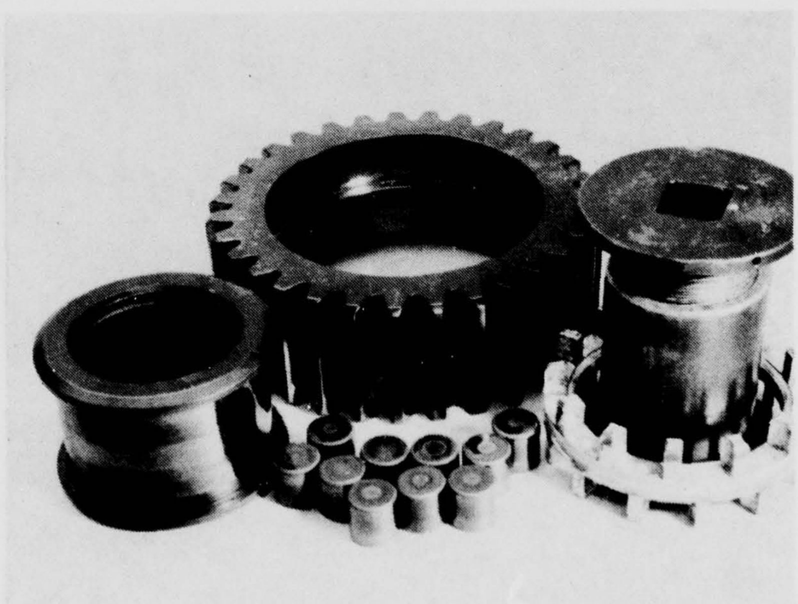


Figure 74. Upper planetary pinion, bearing inner race, rollers, retainer, and roller guides after 19-minute loss-of-lube test of transmission number 2.

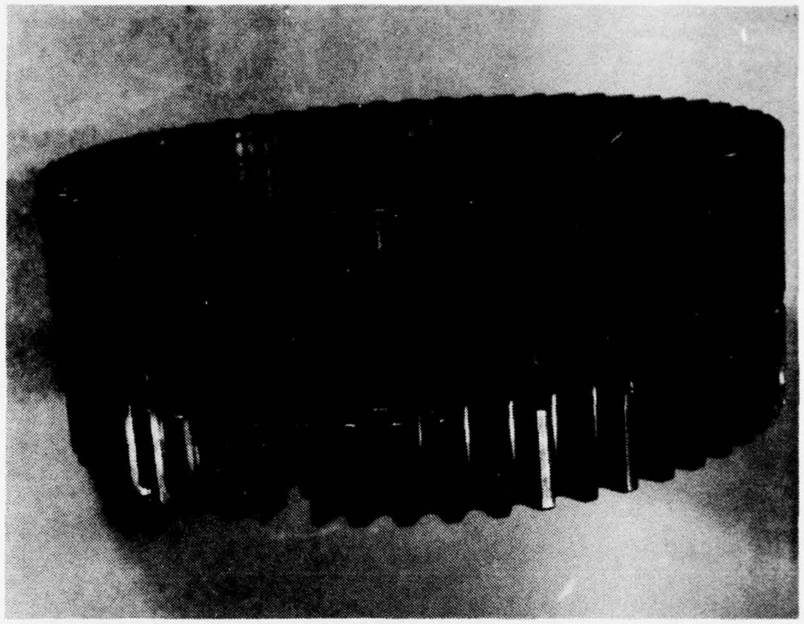


Figure 75. Upper sun gear after 19-minute loss-of-lube test of transmission number 2.

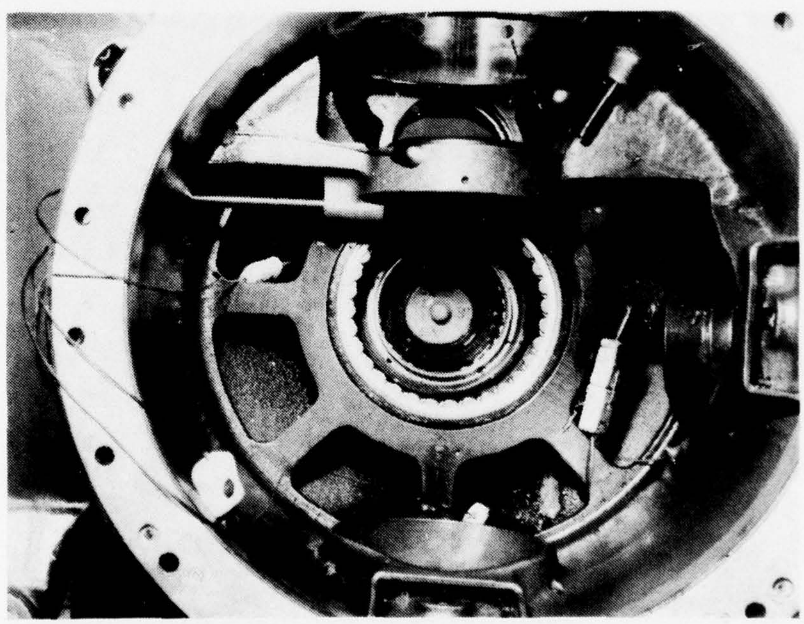


Figure 76. View looking into main and support cases after 19-minute loss-of-lube test of transmission number 2.

Figure 77. Main input pinion teeth (drive side) showing moderate scoring after 19-minute loss-of-lube test of transmission number 2.

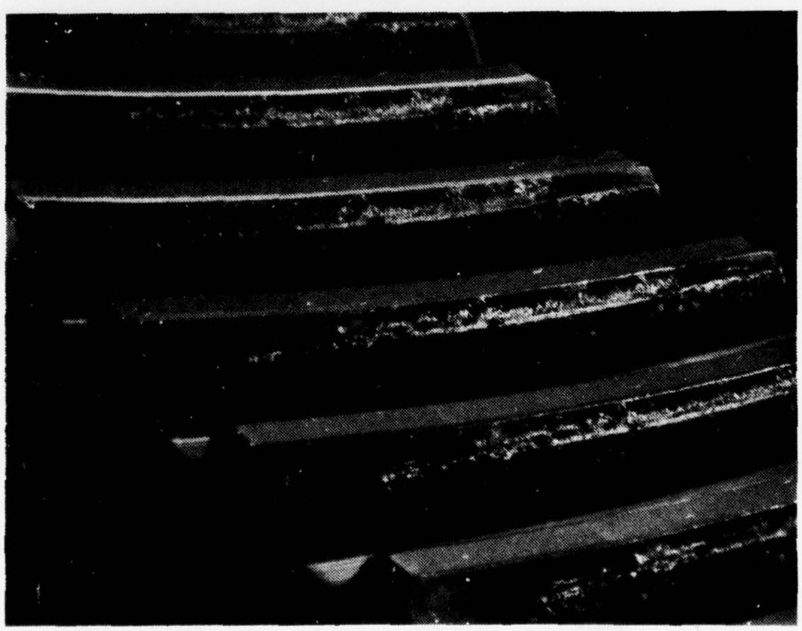


Figure 78. Main input gear teeth (drive side) showing moderate scoring after 19-minute loss-of-lube test of transmission number 2.

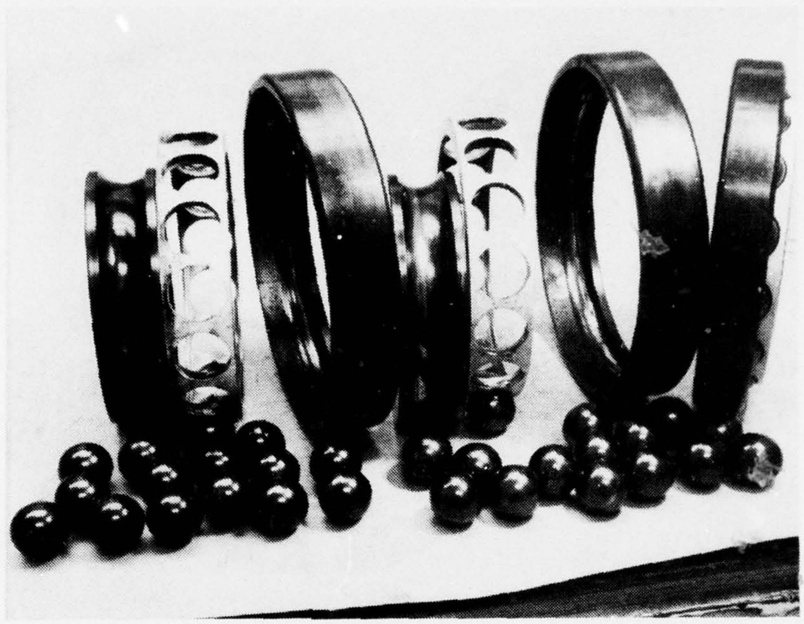


Figure 79. Main input triplex bearing after 19-minute loss-of-lube test of transmission number 2.

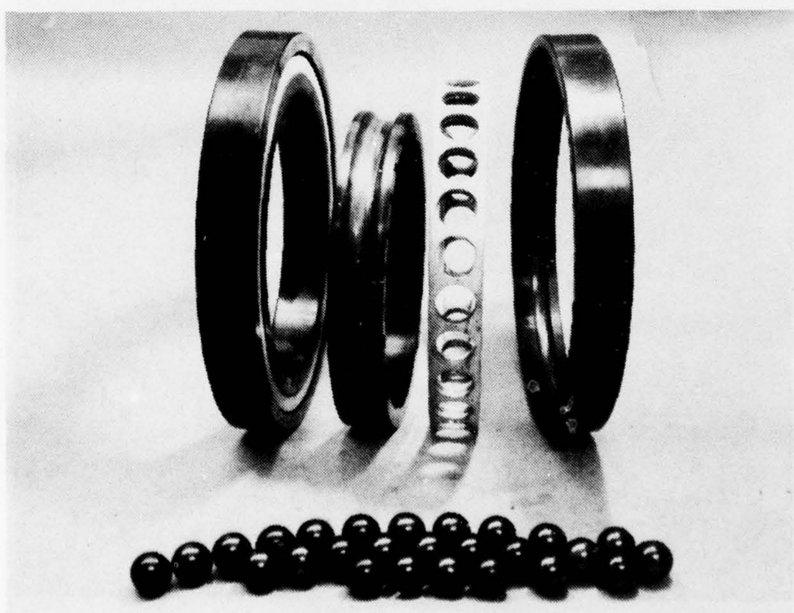


Figure 80. Main gearshaft duplex bearing after 19-minute loss-of-lube test of transmission number 2.

Figure 81. Fan accessory drive duplex bearing showing melted nylatron retainer after 19-minute loss-of-lube test of transmission number 2.

Figure 82. Tail rotor drive, sump input gear (drive side) showing light scoring after 19-minute loss-of-lube test of transmission number 2.

M-50 steel) had a bluish tint as a result of the high temperature operation but the bearings still turned smoothly and, seemingly, suffered no real damage. The duplex ball bearing which supports the main input gearshaft was still functional when removed but had suffered debris damage and turned roughly. The balls of the duplex bearing (made of M-50 steel) also had a bluish tint as a result of the high temperature operation.

The fan drive accessory quill which is located on the forward side of the main case and driven by the main input gear (204-040-701-1) utilizes a duplex ball bearing with a nylatron retainer. The nylatron retainer in the inboard bearing of this duplex pair had melted during the 19-minute loss-of-lube run (reference Figure 81). The bearing was still operational, however, and the fan operated until transmission operation ceased.

The tail rotor drive spiral bevel gear set located in the sump area was scored slightly. Both gears and bearings were still oily in the sump area and, aside from the slightly-scored condition of the gear set, no other damage was apparent.

7.4 DISCUSSION OF RESULTS OF TRANSMISSION NUMBER 2 TESTING

The 19-minute loss-of-lube test of transmission number 2 indicated that the goal of 30 minutes of loss-of-lube operation of an AH-1S transmission could only be achieved through further effort to extend the loss-of-lube capability of the lower planetary stage. It appeared that the 30-minute capability had been achieved for all other transmission components.

It was not possible to ascertain the primary mode of failure in the lower planetary stage by examining the failed components. The failure had progressed to such an extent that both gears and bearings were badly deformed and no specific causations could be positively established. Since the inception of this program it had been suspected that the relatively small planetary gear mesh clearances, which are standard on the AH-1S, might not be sufficient for loss-of-lube operation. After the 21-minute loss-of-lube retest of transmission number 1 which utilized standard AH-1S planetary gear mesh clearances, it was surmised that failure was due to loss of gear mesh clearances in the lower planetary stage. This assumption seemed consistent with the data available. The reason gear mesh clearances were not a problem during the 4.0-hour loss-of-lube run of the AH-1G HST (reference USAAMRDL-TR-76-8), was that the emergency lubrication system, which was operative during the first 1-1/2 hours of the 4.0-hour run, allowed the gears, bearings, and cases to heat up uniformly and thus clearances were maintained. The BHT Model 214 transmission that demonstrated over 1-1/2 hours of loss-of-lube operation, at 75 percent of its maximum takeoff power rating, had nominal gear mesh clearances in the lower planetary of .012 inch which compared to .005 inch for the AH-1S lower planetary. This information seemed to indicate that increasing the AH-1S planetary gear mesh clearances would be beneficial in extending the loss-of-lube capability of the transmission. Transmission number 2 utilized increased clearances in the planetary stages and yet no increase in loss-of-lube run time was demonstrated. Thus it must be concluded that the mode of failure for the loss-of-lube test of transmission number 1 and transmission number 2 was not loss of planetary gear mesh clearances.

One possible explanation for the planetary failure after only 19 minutes of loss-of-lube operation was that both the lower planetary pinions as well as the lower sun gear were carburized gears. Under the high temperatures of loss-of-lube operation, the carburized teeth of the lower planetary pinions and sun gear softened and deformed due to high loads. This resulted in more heat generation, further degradation, and rather rapid gear failure. It was surmised that if the sun gear had been nitrided instead of carburized (a nitrided steel has better hot-hardness characteristics than a carburized steel), the failure would most likely have been significantly delayed. The nitrided sun gear teeth would have retained their involute form at high temperatures and would have encouraged the mating carburized planetary pinion teeth to maintain their form. The degradation process would thus have been slowed.

Another possible explanation for the lower planetary stage failure was that the primary failure mode was loss of clearance in the planetary roller bearings. Nominal clearance in the standard bearing is only .0007 inch. Actual measured clearances in the lower planetary bearings of transmission number 2 ranged from .00067 inch to .00107 inch. It is conceivable that these bearings lost their internal clearances when the transmission was operating under the large thermal gradients of loss-of-lube operation. However, one is tempted to conclude that the planet pinion with its three heat sources (the bearing outer race and the two gear meshes) expanded more rapidly than the bearing inner race and thus this bearing did not fail due to loss of clearance. Unfortunately, the inner and outer races of the lower planetary bearing could not be instrumented with thermocouples and thus the actual thermal conditions which occurred during loss-of-lube operation are unknown. For this reason loss of the lower planetary roller bearing clearance could not be ruled out as the primary mode of failure.

7.5 RATIONALE FOR FOURTH TEST CONFIGURATION

The BHT Model 214 transmission was run on a bench test rig for over 1-1/2 hours under loss-of-lube conditions at 75 percent of its maximum takeoff power rating[3]. The 214 transmission is larger than the AH-1S transmission but the basic designs of the two transmissions are very similar. Each transmission consists of a spiral bevel gear set at the main input from the engine which drives the main rotor mast through two planetary stages. In view of the excellent loss-of-lube performance of the Model 214 transmission and the similarities between the Model 214 and AH-1S transmissions, it was logical to use the design of the Model 214 lower planetary stage as a guide to improve the survivability of the AH-1S lower planetary. The Model 214 planetary stages utilize large gear mesh clearances (comparable to those used in the planetaries of transmission number 2 of this program). The Model 214 has lower planetary roller bearings with silver-plated steel retainers and nominal internal clearances of .0012 inch, compared to nominal internal clearances of .0007 inch for the standard AH-1S lower planetary roller bearings. The Model 214 transmission has a nitrided lower sun gear whereas the standard AH-1S lower sun gear is carburized. The advantage of a nitrided lower sun gear with its improved hot-hardness characteristics was discussed previously. The planetary stages of the Model 214 have steel ring gears splined into an aluminum case as opposed to the AH-1S steel ring gears which are an integral part of the steel ring gear case. Since the thermal conductivity of aluminum is about four times greater than steel, the Model 214 ring gear arrangement is probably much better for loss-of-lube operation because of its ability to dissipate more heat. Another facet of the Model 214 transmission which is probably beneficial for successful loss-of-lube operation is the compartmentalization of the transmission to improve chip detection and to prevent debris generated to one area of the transmission from contaminating other areas. As a part of this system, a debris collector is installed beneath the gear shaft support case which is just below the lower planetary stage of the 214 transmission. This debris collector catches the oil returning from the planetary and retains some of this oil even after the main lubrication system has been lost. The oil thus retained is blown about by the windage of the planetary stages and in this in way helps to maintain lubricated contacts.

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[3] D. J. Richardson, and J. H. Drennan, THE OPERATION OF BELL DRIVE SYSTEMS FOLLOWING THE LOSS OF LUBRICATION, presented at the 32nd National Annual Forum of the American Helicopter Society, Washington, D.C., May 1976.

In conjunction with the AH-1S lower planetary modifications previously tested during this program, the following improvements, suggested by the design of the Model 214, were utilized in the fourth test configuration of the AH-1S HST.

- A nitrided lower sun gear was used in place of the standard, carburized lower sun gear.

- Lower planetary roller bearing clearances were increased nominally from .0007 inch to .0012 inch.

- Lower planetary bearing inner races were made of M-50 steel instead of AISI 52100 steel.

- Oil pockets were installed just below the lower planetary stage to trap oil for use during loss-of-lube operation.

8. AH-1S HST FOURTH TEST

8.1 GENERAL OBJECTIVES

The objective of the fourth test conducted under this program was to determine the response of the fourth transmission configuration to the complete loss of the oil supply.

8.2 TEST PROGRAM, FOURTH TEST

8.2.1 Fourth Test Transmission Configuration

In order to build up a transmission for the fourth test, used components from the two transmissions already tested as well as used components from a previous test effort (conducted under Contract DAAJ01-74-C-0403) were utilized. Since the parts from these previously tested transmissions had already been subjected to some abusive operation, there was a slight risk involved in reusing these components. Parts reused were visually scrutinized and some were dimensionally inspected in an effort to minimize the risk.

Table 1 defines the bearing changes for the fourth test and Table 6 defines the significant gear mesh backlash measurements. In addition to the modifications indicated by Tables 1 and 6, the changes listed below were made to the standard AH-1S transmission configuration.

- A carbon radial seal was installed in the main input quill in place of the standard elastomeric radial lip seal.
- A nitrided lower sun gear was used in place of the standard carburized lower sun gear. (A spacer was fabricated to adapt the 209-040-031-1 nitrided sun gear to the AH-1S transmission.)
- Six oil collecting cups were installed in the main spiral bevel gear support case located directly below the lower planetary stage. (The oil collectors are shown installed in the support case in Figure 83.)

Thermocouple locations for this test were as listed in Table 2 and shown in Figure 2. The three thermocouples on the inner races of the triplex bearing and the thermocouple in the root of the input pinion were not used for this fourth test. An oil drainage system shown schematically in Figure 3 was also installed.

8.2.2 Description of Tests

The assembled transmission was green run according to the load and speed schedule of Table 3 in order to meet the following specific objectives:

- To verify proper assembly and to give the new parts a break-in period.
- To check out all instrumentation.
- To verify that the new nitrided sun gear with its associated spacer would operate normally.

No thermal testing was conducted during the fourth test program. A loss-of-lube test was performed according to the load and speed schedule of Table 8 to determine the response of the transmission to loss of the bypass valve and/or the lower part of the sump which would result in the loss of the main oil supply.

8.3 RESULTS OF THE FOURTH TEST PROGRAM

8.3.1 Results of Green Run

The green run was completed per the load and speed schedule of Table 3. The post-green run inspection indicated that the transmission was functioning normally. The only unusual condition noted after the green run was the appearance of the roller bearing journal of the main input pinion. Figure 84 is a photograph of this journal after the green run but prior to the loss-of-lube test. As was noted earlier, the transmission for the fourth test was assembled with previously used components. The main input pinion roller bearing journal had slight traces of rust which were cleaned off prior to initial build up. The rust damage accounts for the appearance of the journal after green run. It was felt that the bearing journal was not damaged severely enough to affect the results of the loss-of-lube test and therefore the transmission was reassembled without replacing any components.

8.3.2 Results of Fourth Loss-of-Lube Test

The fourth loss-of-lube test was conducted according to the load and speed schedule of Table 8. The test transmission was operated at 950 hp (84 percent of MCP) under normal lubrication conditions until the oil inlet temperature stabilized at 230°F. Then, with the transmission still operating at 950 hp with 30 hp through the tail rotor, and lift and bending loads applied to the main rotor mast, valve C was opened and valves A and B were closed (reference Figure 3) allowing the oil to be pumped

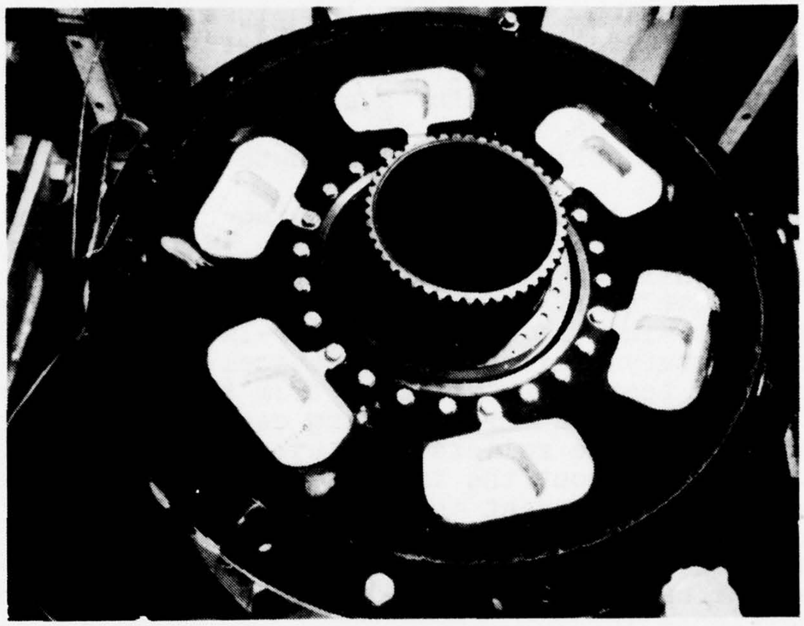

Figure 83. View of gearshaft support case showing oil collectors installed prior to green run for fourth test.

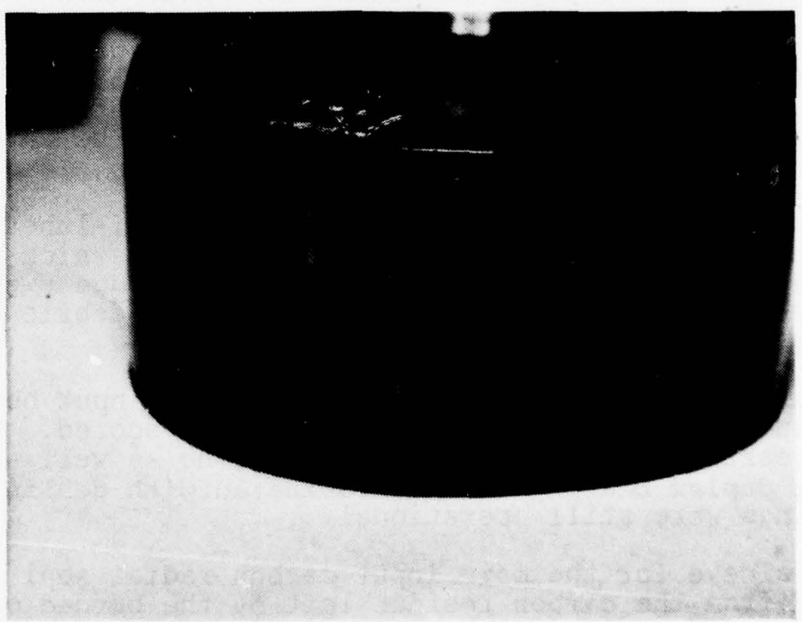

Figure 84. Input pinion roller bearing journal showing rust damage after green run prior to fourth loss-of-lube test.

from the transmission. After complete loss of the main oil supply, the transmission continued to operate for 26.5 minutes before torque was lost due to failure of the lower planetary stage. Transmission temperatures at failure are shown in Figure 85. Figures 86 through 95 show temperature plots of various components during the 26.5-minute run.

Disassembly of the transmission following the 26.5-minute loss-of-lube test revealed that the planetary failure was similar to the planetary failures which had occurred on the two previous loss-of-lube test runs. Figures 96 through 116 show various components following the fourth loss-of-lube test. All four of the lower planetary pinions were plastically deformed and misshapen. The teeth were stripped from the lower planetary pinions. The lower planetary bearing cages were bent and broken and many of the rollers were ejected from the bearing and scattered throughout the transmission. Some of the rollers were ground up as they went through the planetary gear meshes. The nitrided lower sun gear fared better than the carburized lower sun gears of the previous tests; however, the center portion of the nitrided gear teeth were somewhat deformed (reference Figure 102).

The upper planetary stage was heavily damaged by debris from the lower stage but was still functional. The upper planetary gear teeth showed no signs of having lost gear mesh clearance. The upper sun gear teeth were debris damaged but not plastically deformed. Both the upper and lower ring gear teeth were chipped and dented from the debris but the teeth retained their form. The upper and lower planetary support bearings were extremely tight and rough, but they could still be turned by hand.

Both planetary stages were dry after the loss-of-lube test. All of the oil was gone from the oil collectors which had been installed in the gearshaft support case (reference Figure 97) and the support case assembly was damaged from debris carried around by the lower planetary stage.

Metal particles spotted the teeth of the main input bevel set (pinion and gear) and the teeth were lightly scored. The input triplex bearing and the input roller bearing as well as the gearshaft duplex bearing were contaminated with debris, but the bearings were still operational.

The wear sleeve for the main input carbon radial seal was blackened from the carbon residue left by the burned oil; however, there did not appear to be any unusual wear. This was the same seal and wear sleeve that had been used during the testing of transmission number 2.

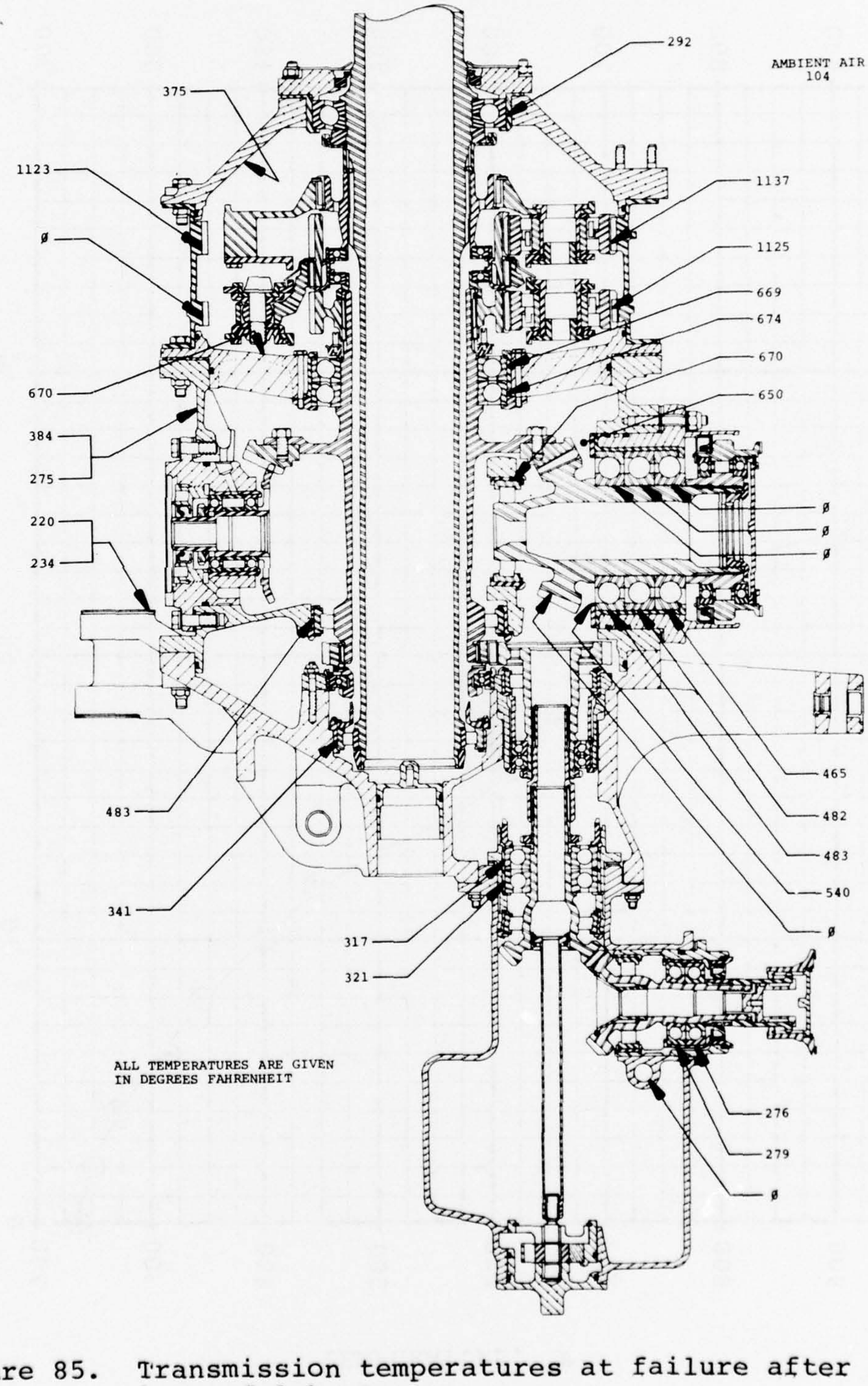

Figure 85. Transmission temperatures at failure after fourth loss-of-lube test.

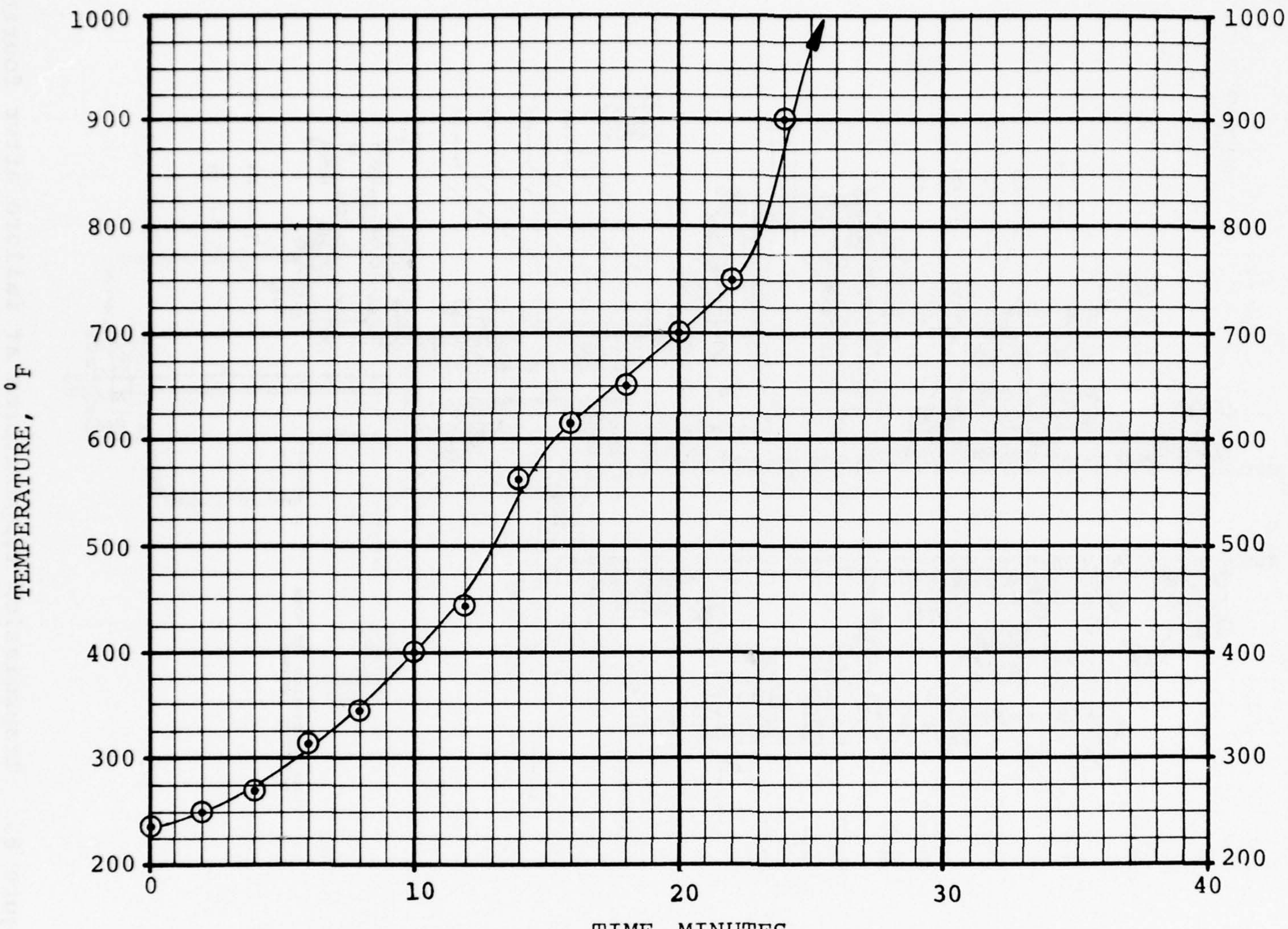

Figure 86. Lower ring gear temperatures during fourth loss-of-lube test. (thermocouple no. 11)

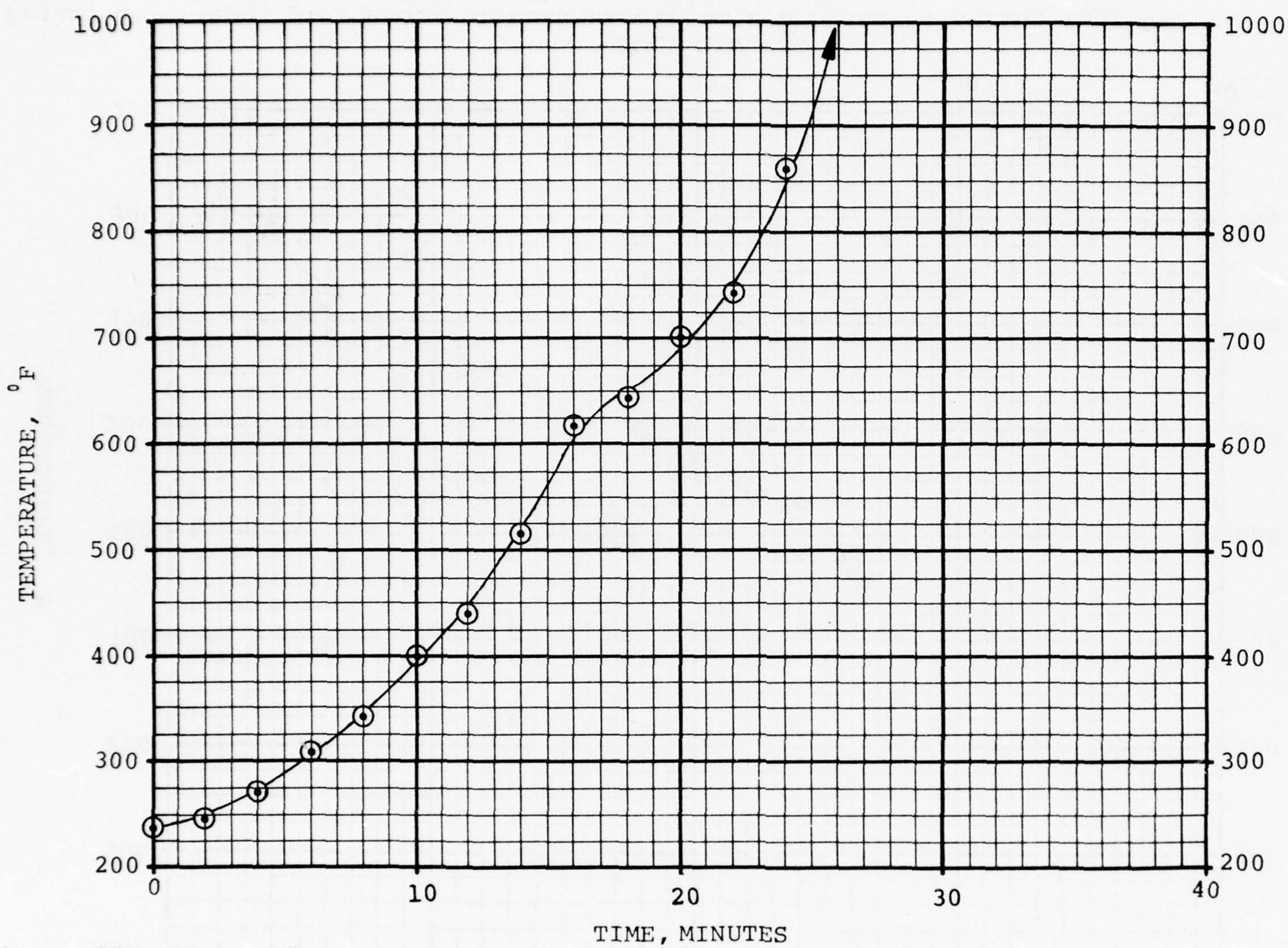

Figure 87. Upper ring gear temperatures during fourth loss-of-lube test. (thermocouple no. 10)

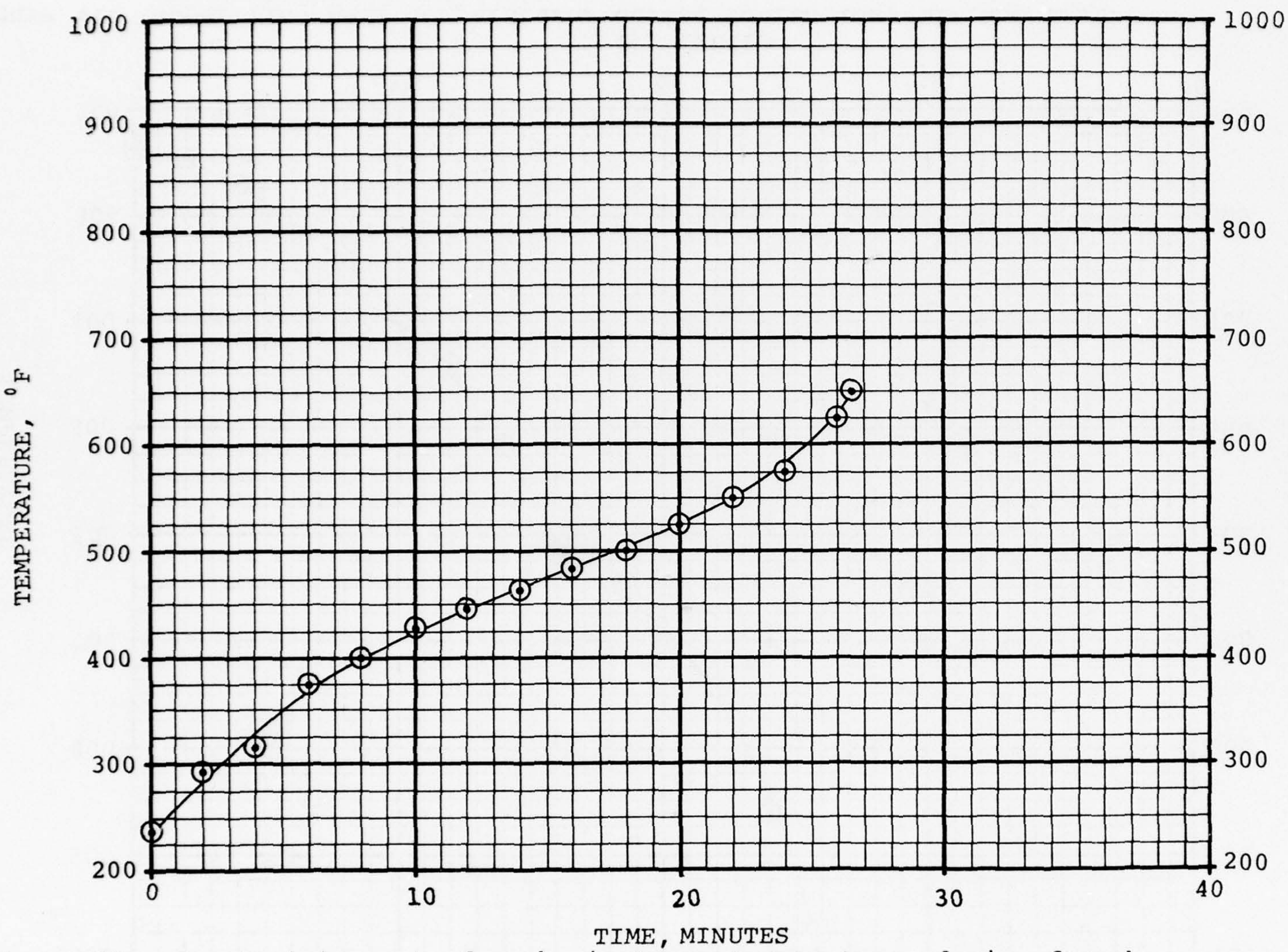

Figure 88. Input pinion out-of-mesh airstream temperatures during fourth loss-of-lube test. (thermocouple no. 32)

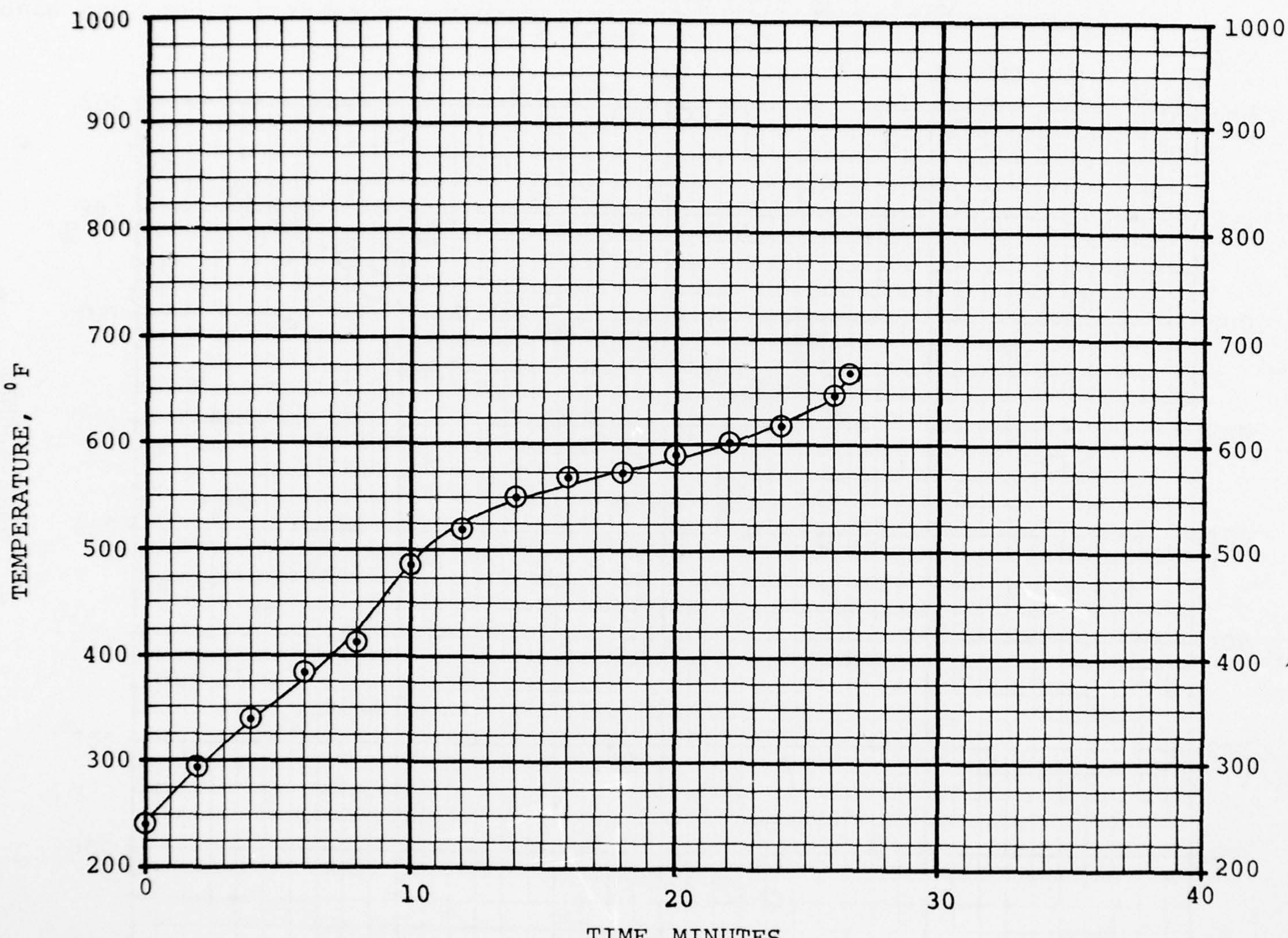

Figure 89. Input pinion roller bearing outer race temperatures during fourth loss-of-lube test. (thermocouple no. 5)

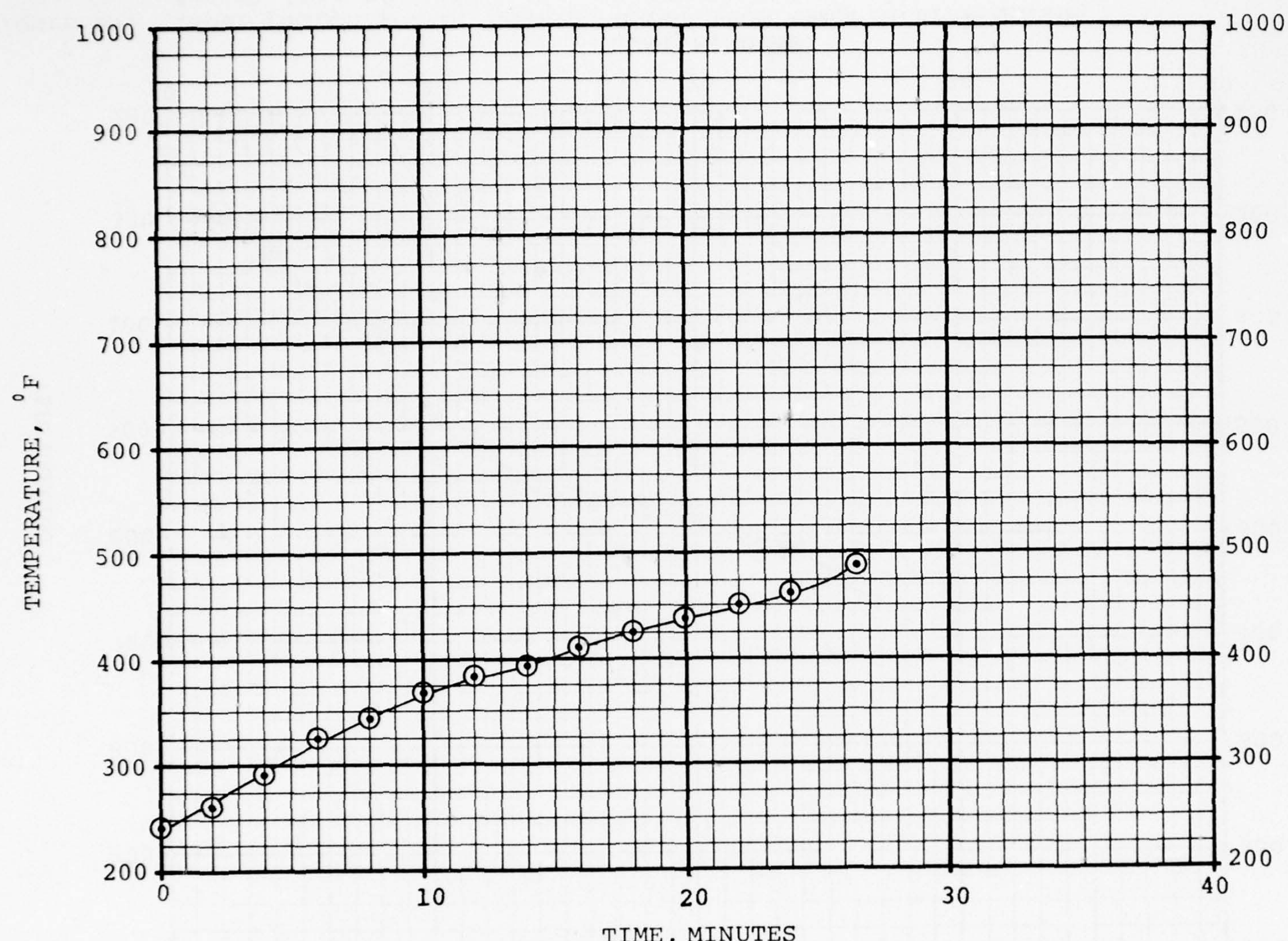

Figure 90. Input triplex inboard bearing outer race temperatures during fourth loss-of-lube test. (thermocouple no. 18)

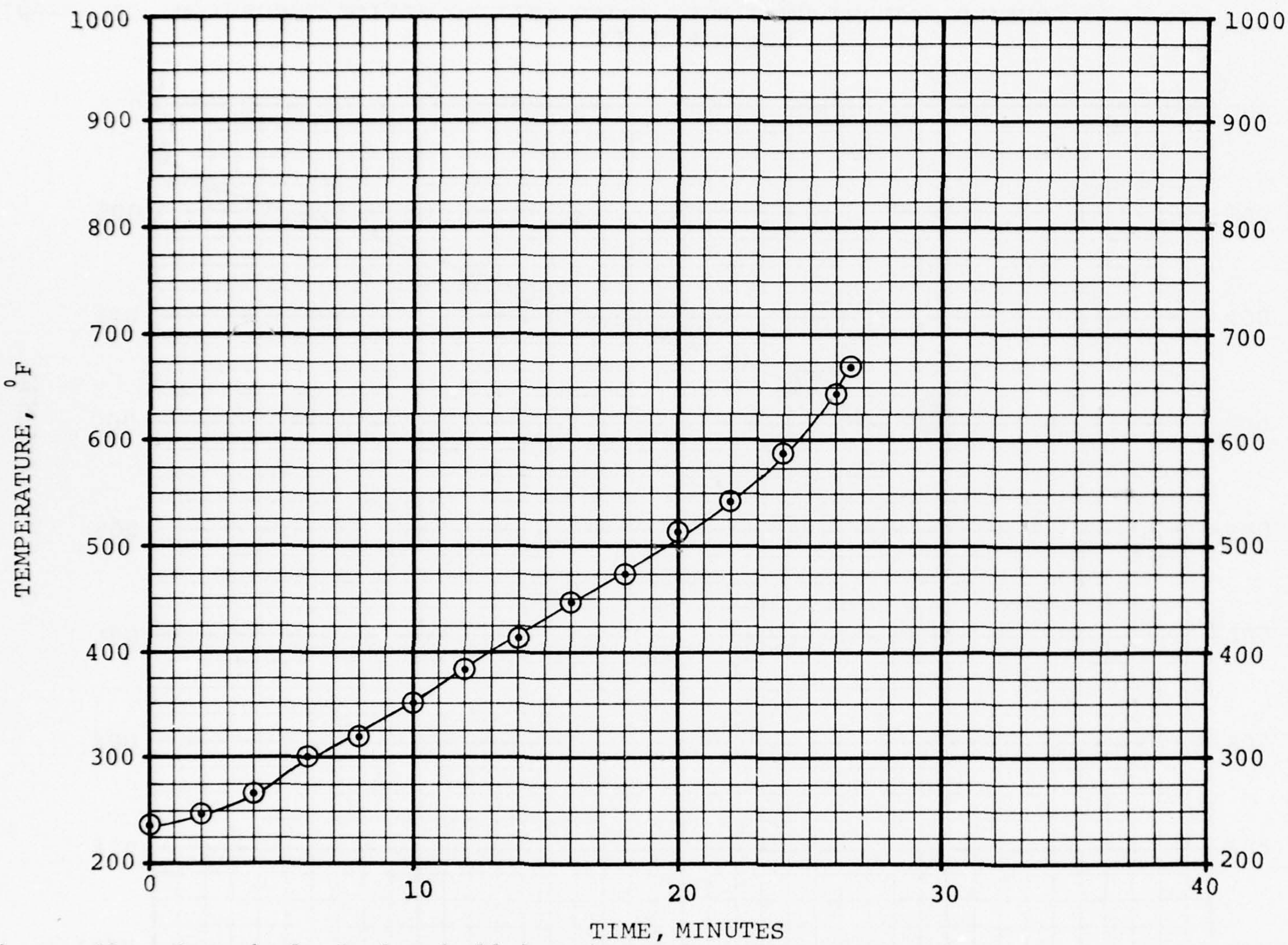

Figure 91. Gearshaft duplex ball bearing outer race temperatures during fourth loss-of-lube test. (thermocouple no. 3)

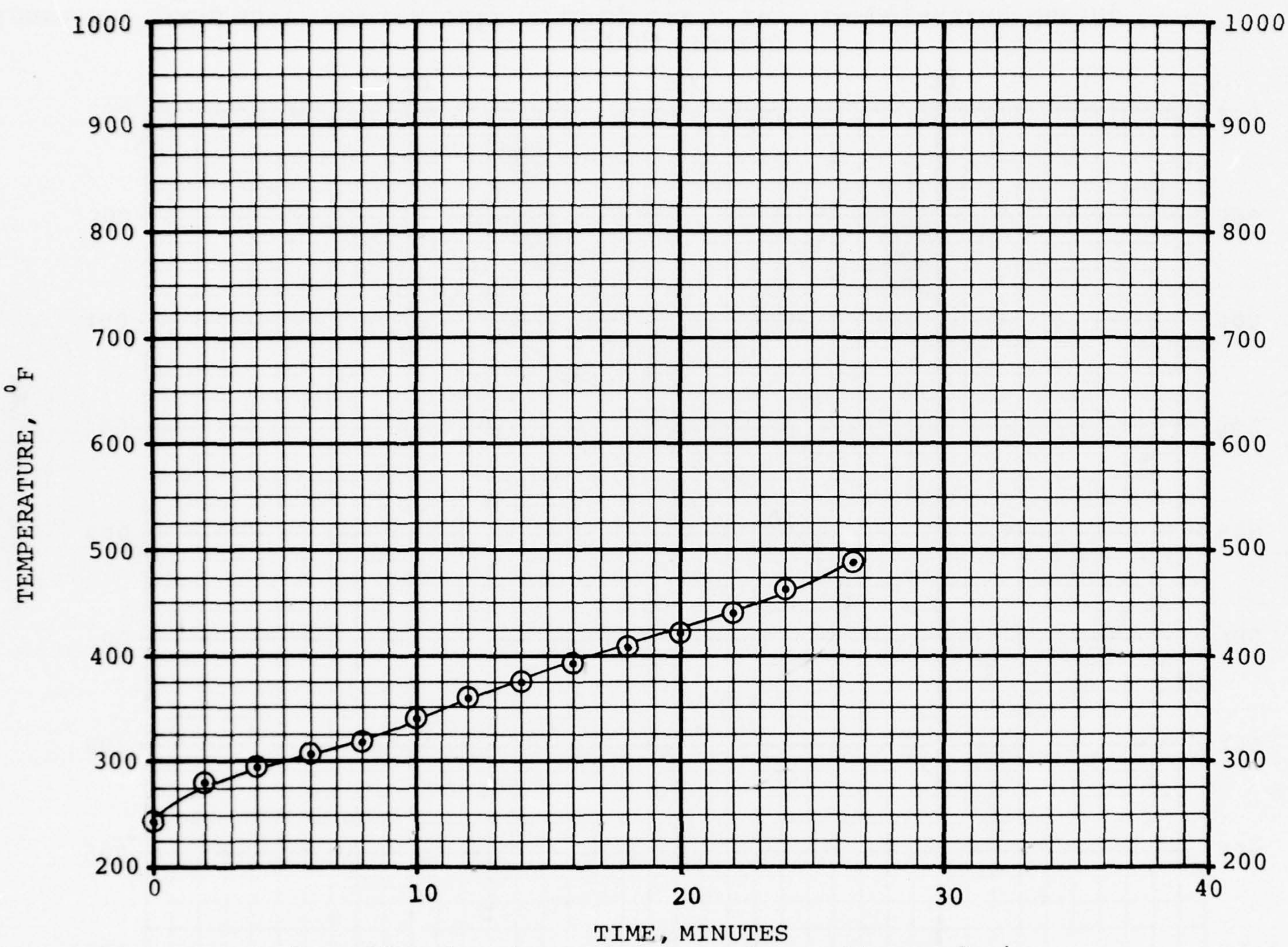

Figure 92. Gearshaft roller bearing outer race temperatures during fourth loss-of-lube test. (thermocouple no. 6)

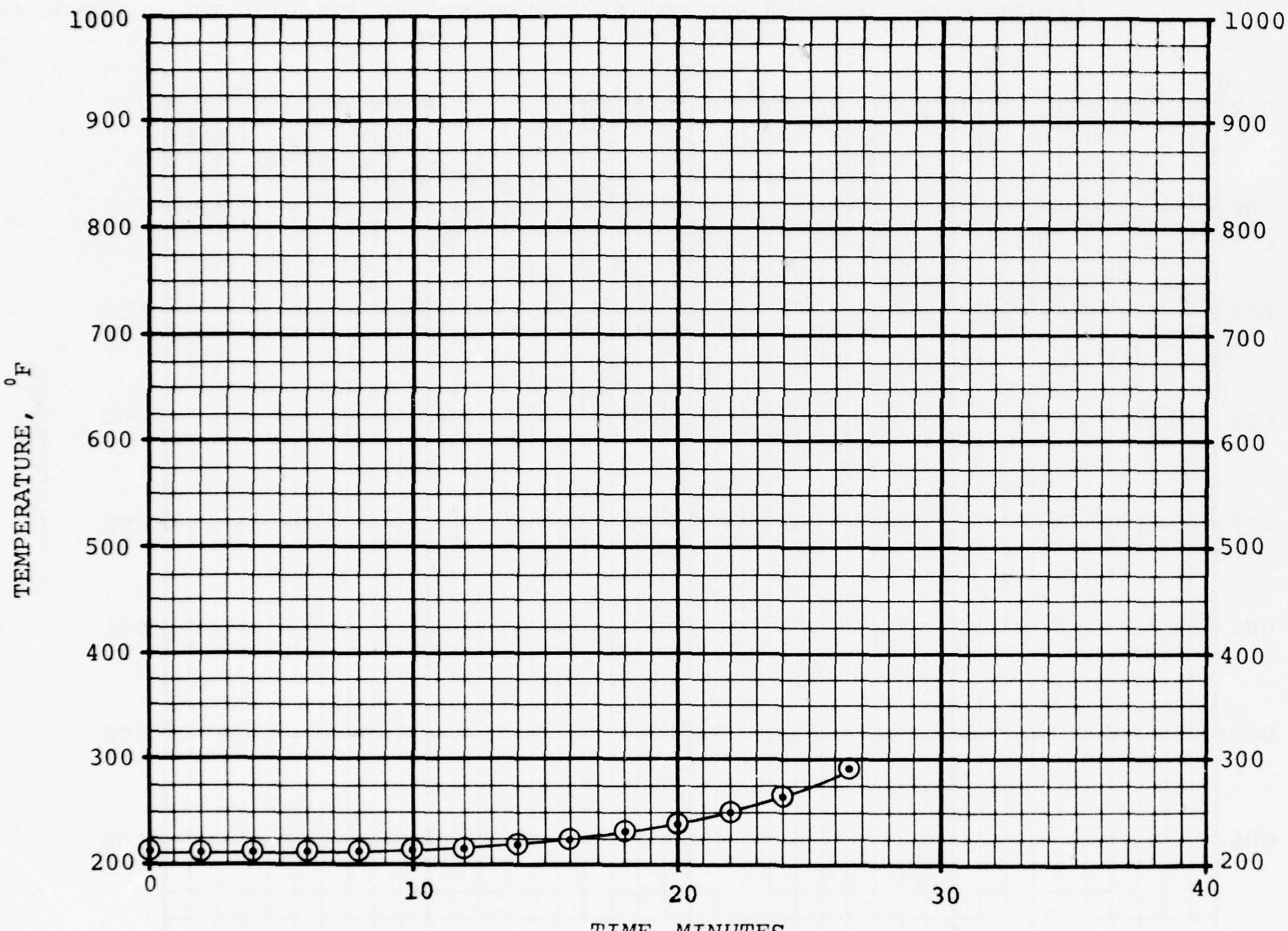

Figure 93. Upper mast ball bearing outer race temperatures during fourth loss-of-lube test. (thermocouple no. 31)

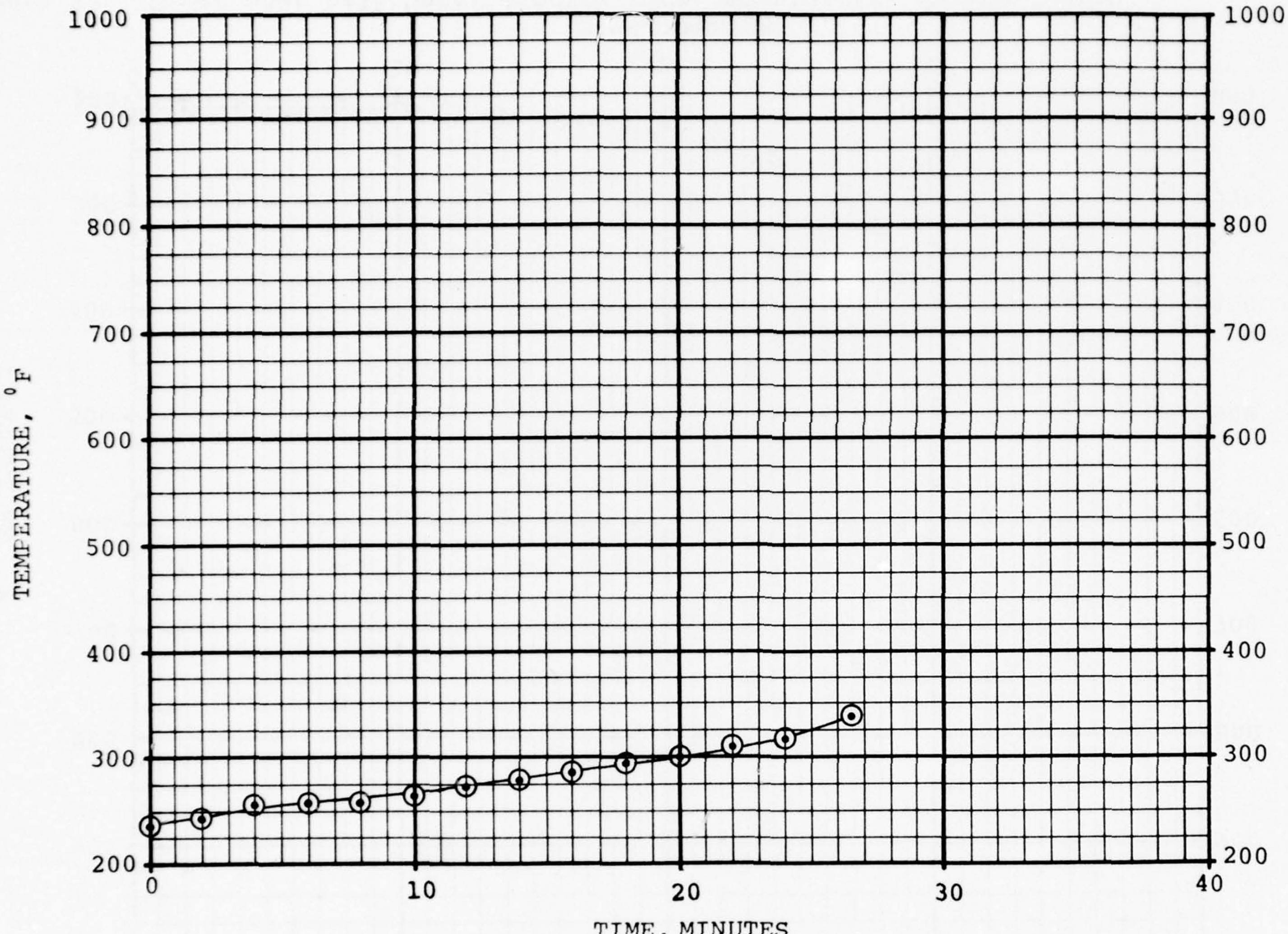

Figure 94. Sump input, duplex bearing outer race temperatures during fourth loss-of-lube test. (thermocouple no. 14)

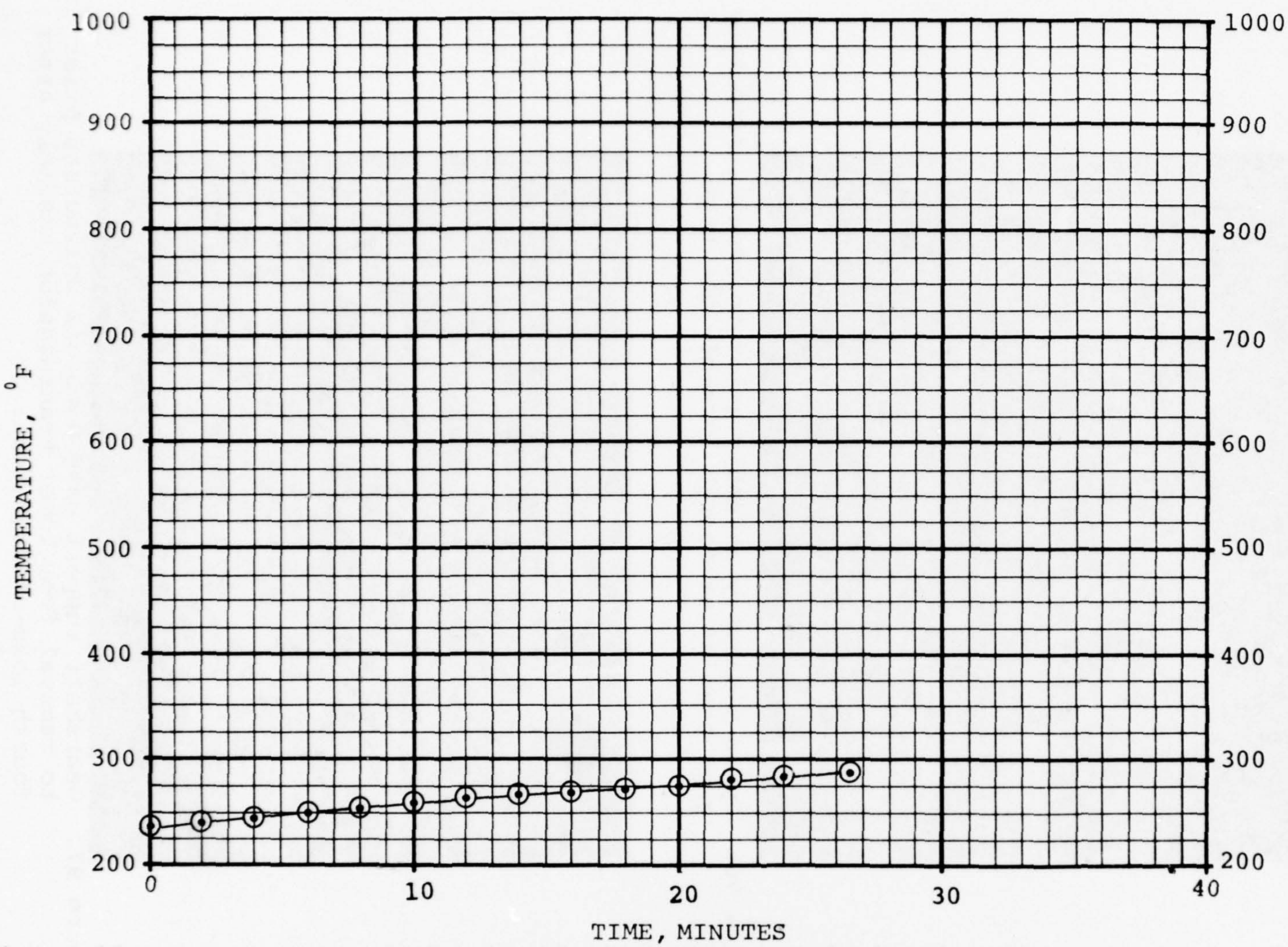

Figure 95. Sump output, duplex bearing temperatures during fourth loss-of-lube test. (thermocouple no. 16)

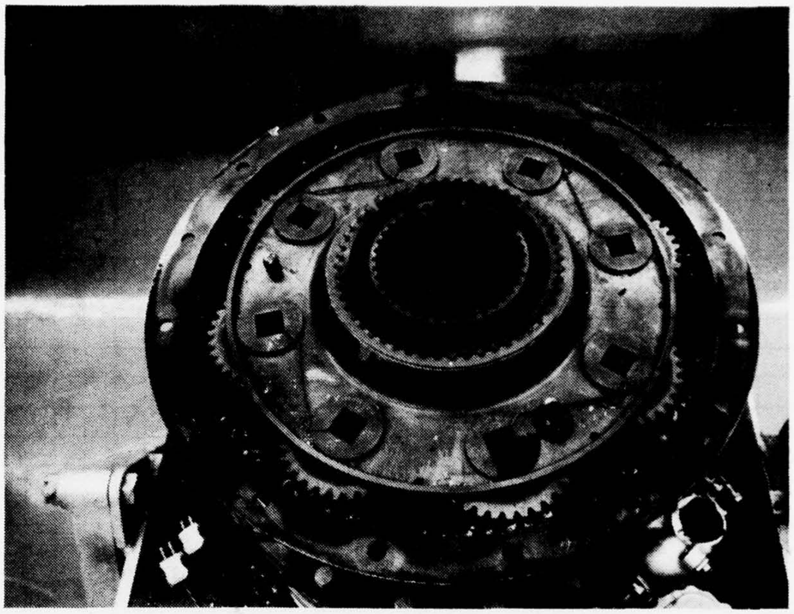

Figure 96. Upper planetary assembly prior to removal from ring gear case after fourth loss-of-lube test.

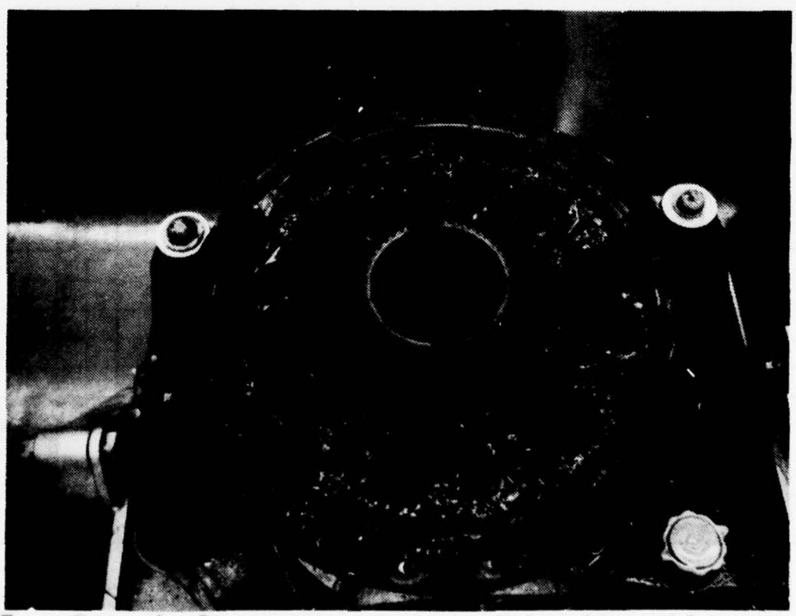

Figure 97. Gearshaft support case with oil collectors prior to removal from lower transmission assembly after fourth loss-of-lube test.

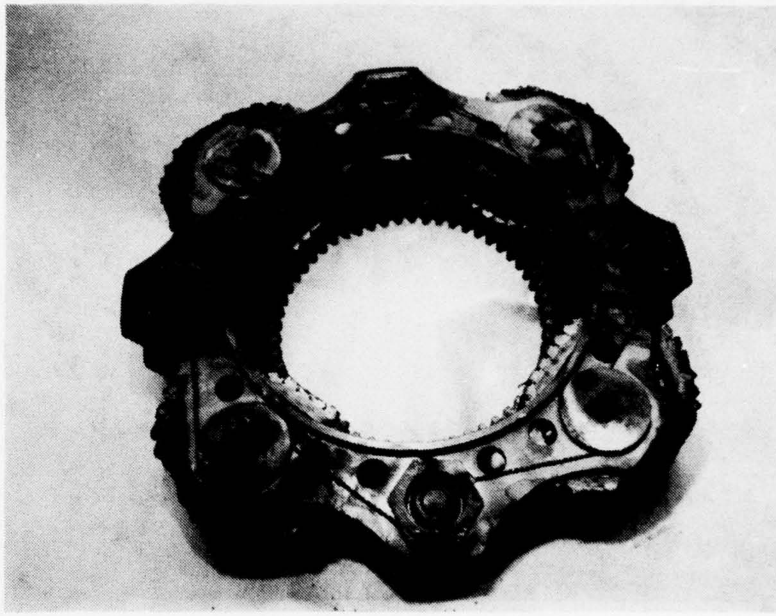

Figure 98. Lower planetary assembly after fourth loss-of-lube test.

Figure 99. Lower planetary pinion, bearing, inner race, rollers, retainer, and roller guides after fourth loss-of-lube test.

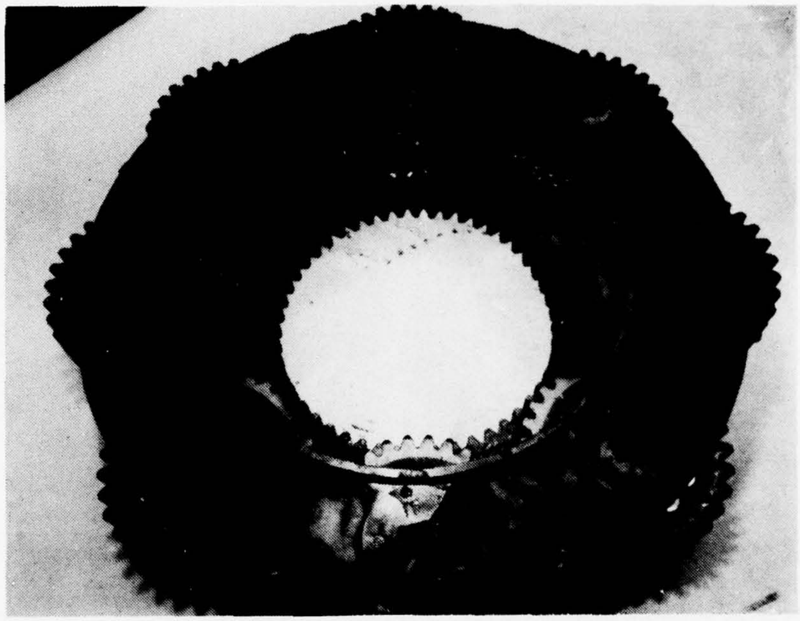

Figure 100. Upper planetary assembly after fourth loss-of-lube test.

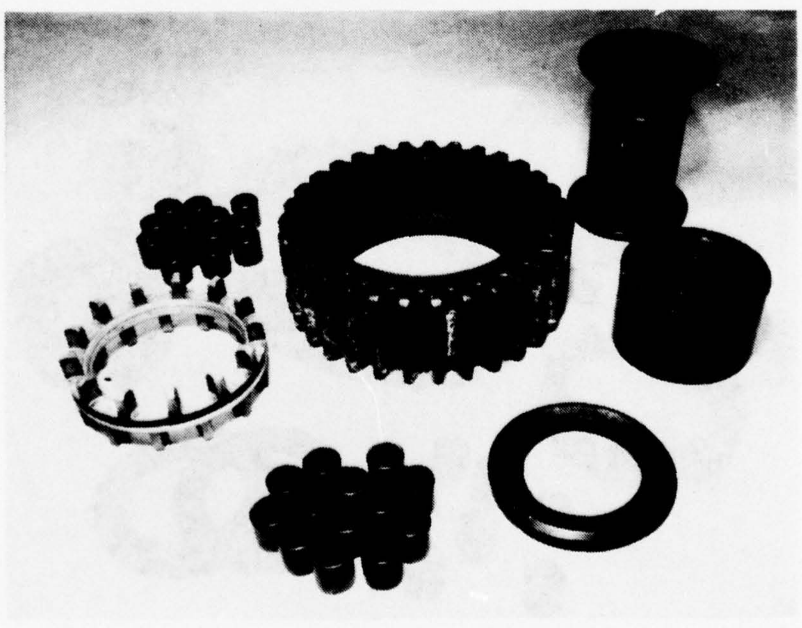

Figure 101. Upper planetary pinions, bearing inner race, rollers, retainer, and roller guides after fourth loss-of-lube test.

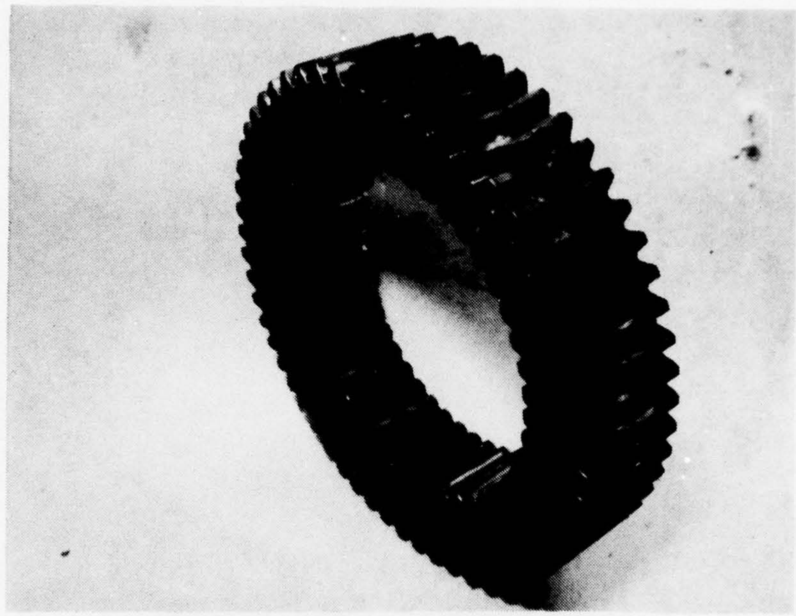

Figure 102. Nitrided lower sun gear after fourth loss-of-lube test.

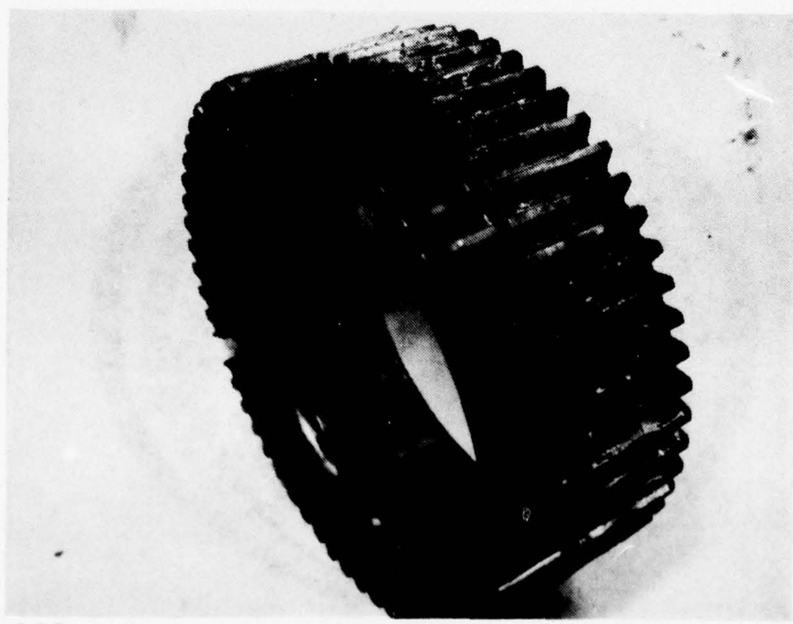

Figure 103. Upper sun gear after fourth loss-of-lube test.

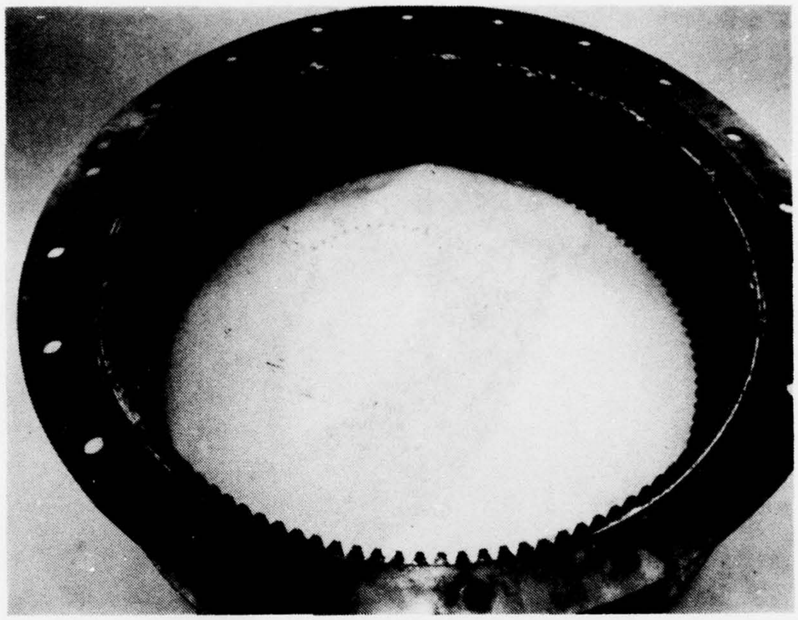

Figure 104. Ring gear case following fourth loss-of-lube test.

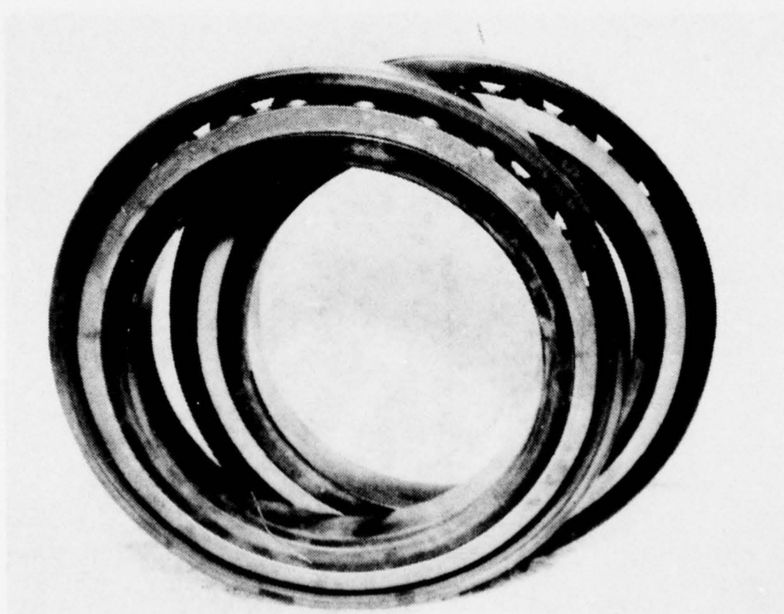

Figure 105. Input gearshaft duplex bearing after fourth loss-of-lube test.

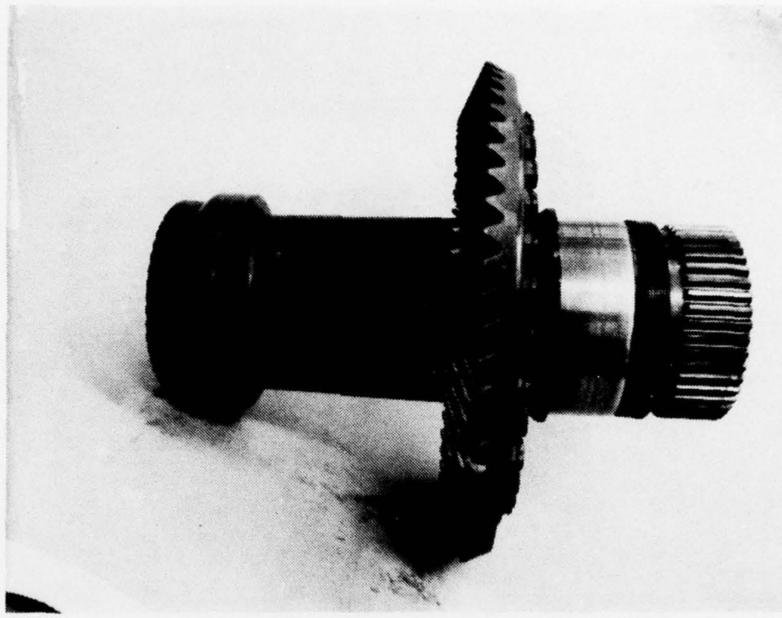

Figure 106. Main input gear and gearshaft after fourth loss-of-lube test.

Figure 107. Main input gear teeth after fourth loss-of-lube test.

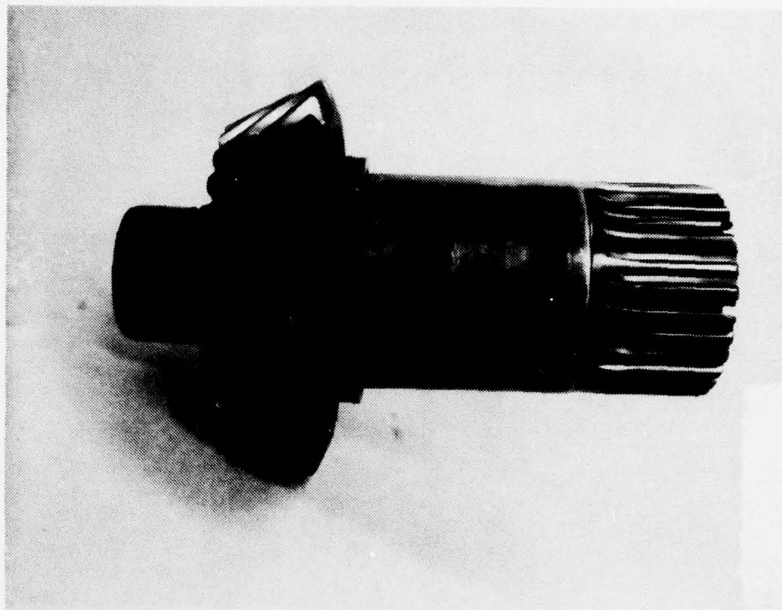

Figure 108. Main input pinion after fourth loss-of-lube test.

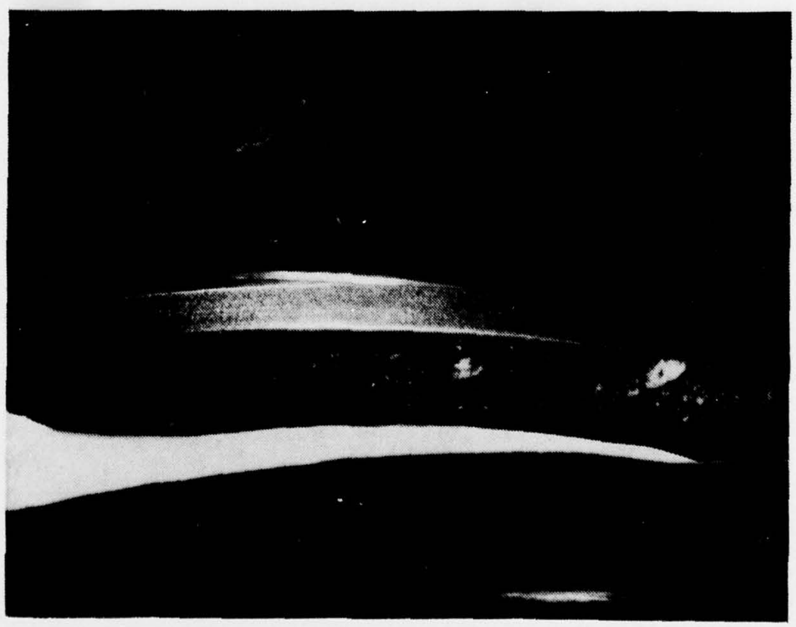

Figure 109. Main input pinion teeth after fourth loss-of-lube test.

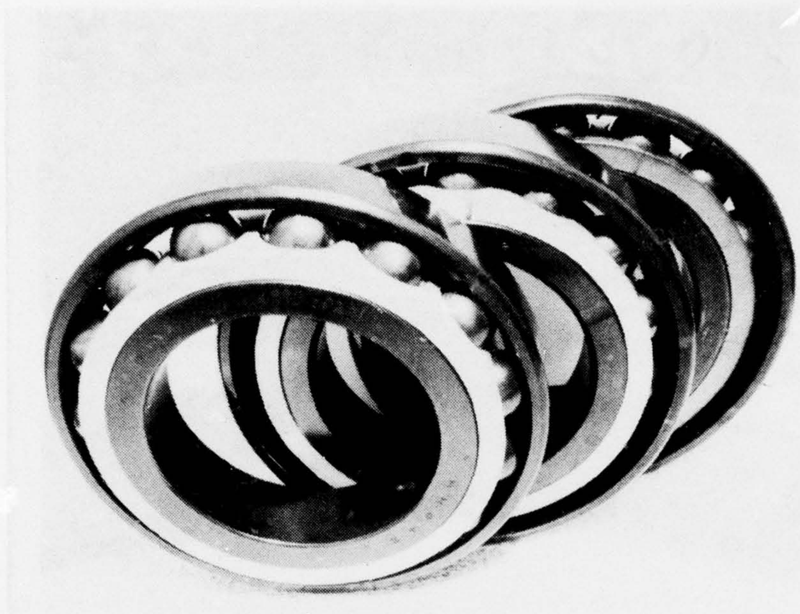

Figure 110. Main input triplex bearing following fourth loss-of-lube test.

Figure 111. Input pinion roller bearing following fourth loss-of-lube test.

Figure 112. Main input carbon radial seal after fourth loss-of-lube test.

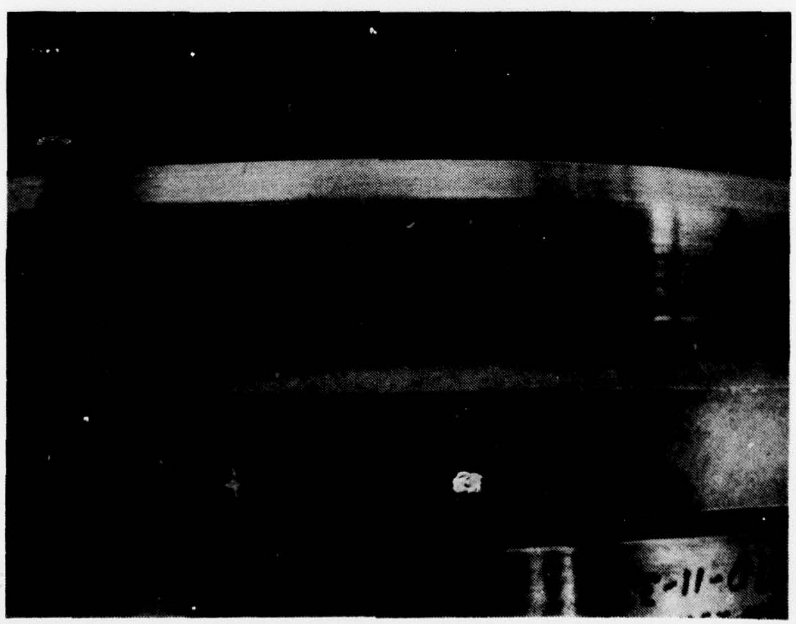

Figure 113. Main input seal wear sleeve after fourth loss-of-lube test.

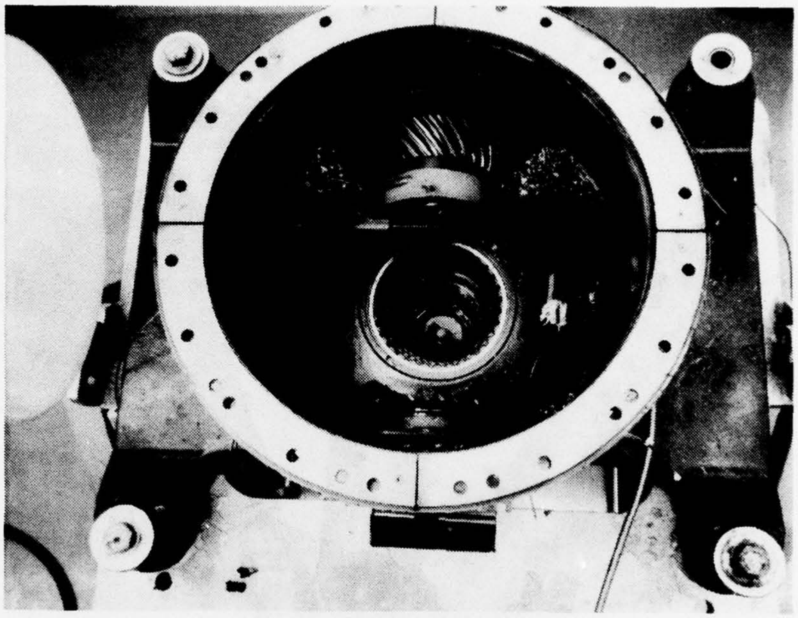

Figure 114. View looking into main case after fourth loss-of-lube test.

Figure 115. Fan accessory drive duplex bearing after fourth loss-of-lube test.

Figure 116. Sump input, output, and hydraulic pump drive gears (left to right, respectively) after fourth loss-of-lube.

The nylatron retainer of the inboard bearing of the fan accessory drive duplex bearing melted and failed just as did the fan accessory drive duplex bearing of transmission number 2. The bearing was still operational even with the failed cage.

The lower portion of the main transmission which includes the tail rotor drive system was still oily when the transmission was disassembled. There was some slight debris damage to the gears and bearings in the tail rotor loop; however, the gears were not scored and the bearings were still bright and shiny with no discoloration.

8.4 DISCUSSION OF RESULTS OF FOURTH TEST

The 26.5-minute loss-of-lube test of the fourth transmission configuration closely approached the 30-minute program goal. It had been hoped, however, that this test transmission would operate for a significant time period beyond 30 minutes to provide a high level of confidence that 30 minutes of loss-of-lube run time could be achieved on an AH-1S helicopter in actual operation. The results of this test program indicate that still more effort is required if this goal is to be achieved. It may be that further internal component modification would be sufficient to achieve the desired loss-of-lube run time; on the other hand, it may be that the desired loss-of-lube run time can only be achieved with an emergency lubrication system or with a major redesign of the transmission.

The fourth loss-of-lube test strengthened the supposition that a 30-minute loss-of-lube capability has been achieved for all transmission components except the lower planetary stage. The post-run inspection of the test transmission indicated that it would have operated successfully for quite some time had the lower planetary failure not occurred.

The lower planetary stage modifications installed in the test transmission for the fourth loss-of-lube run were effective in maintaining transmission operation for more than 10 minutes after the lower ring gear temperature reached 600°F. This was an improvement over the previous two tests in which the transmissions lasted only 4 to 6 minutes once the 600°F lower ring gear temperature was attained. The use of the nitrided lower sun gear, instead of the standard carburized lower sun gear, and the use of M-50 steel lower planetary bearing inner races, instead of the standard AISI 52100 steel inner races, probably accounted for the improved high-temperature performance of the fourth test transmission. Comparing the lower ring gear temperature plot for the fourth test with the lower ring gear temperature plots for the previous two tests (Figure 86 versus Figures 53 and 21), one surmises that the oil trapped by the oil collectors must have been blown about and lost almost immediately and so had little or no effect on the loss-of-lube run time. The lower ring gear temperature seems to be a good indicator of the condition of the modified transmission system when operating without oil.

The lower planetary stage failure of the fourth test transmission was very similar to the lower planetary failures of the previous two tests. As before, the failure had progressed to the point that the exact failure mode was unidentifiable. The combination of high loads and high temperatures forced the failure of the lower planetary pinions. Apparently, at the high temperatures of no-lube planetary operation was the planetary pinions softened and distorted under predesign heavy gear loading, causing increased heat generation at both gear meshes and in the planetary roller bearing. This led to the oblong shape of the pinions and to the failed bearings and gear teeth.

Methods to prolong the loss-of-lube capability of the lower planetary stage must address the problems of reducing temperatures and reducing loads. A number of suggestions may be offered to accomplish this.

The use of oil collectors to trap oil and provide lubricant during lube-loss operation is probably an excellent way to reduce the rate of temperature rise. The oil collectors used for the fourth test under this program were very shallow and consequently, as was discussed earlier, the oil was lost almost immediately after the start of the loss-of-lube run. A more effective oil collector would be an actual debris collector installed beneath the bevel gear support case (similar to the Bell Model 214 transmission). This would not only protect the oil somewhat from the windage of the lower planetary stage but would also insure that all of the oil dripping back from the lower planetary would be again caught by the collector. In order to utilize such a debris collector, a chip detector would have to be installed in the collector pan to detect the presence of chips. An alternative to the debris collector would simply be the use of deep-pocket oil collectors instead of shallow ones as were used for this program.

The distortion and misalignment which occurs in the lower planetary stage serves to concentrate the tooth loads on the ends of the teeth. One way to minimize this type of loading would be to use a lower sun gear with a smaller face width and with crowned teeth. The 204-040-329-1 lower sun gear which was used during the 4.0-hour loss-of-lube test of the AH-1G High Survivable Transmission under Contract DAAJ02-74-C-0019 had a face width of .938 inches, compared to 1.450 inches of face width for the 205-040-229-1 lower sun gear used in this program. Neither of these two gears have crowned teeth. Since the planetary pinion face width is 1.333 inches, the narrow sun gear does not engage the full face width of the planetary pinion. The face width of the lower ring gear teeth is .800 inches and so, with the narrow sun gear installed, the planetary pinion teeth have about .2 inch of face width per side, not contacting either the sun gear teeth or the ring gear teeth. These unloaded areas may tend to help the pinions maintain their shape during loss-of-lube operation. The use of a narrow sun gear would most likely force the failure mode to be the stripping of the lower sun gear teeth. This is a less severe failure mode since it allows the main rotor mast to continue rotation.

Another way of reducing the individual planetary pinion loads would be to use an eight-pinion planetary instead of the standard four-pinion lower planetary. This would cut the gear tooth loads and the bearing loads in half. A weight increase of approximately 14.6 pounds would accompany the installation of the eight-pinion planetary. A 6-percent increase in frictional losses in lubricated operation would also accompany the eight-pinion planetary, and windage and churning losses would be significantly increased. Since the frictional loss equations are based on lubricated operation, one can only speculate what might happen in nonlubricated operation. Perhaps reducing the individual pinion loads would limit distortion to the extent that heat generation would be significantly reduced during the loss-of-lube operation.

Loss-of-lube tests conducted on other gearboxes indicate that loss-of-lube run time is very sensitive to the relative power level at which the gearbox is run. A small decrease in power level will probably result in a large increase in loss-of-lube capability.

Had the testing under this program been conducted at 75 percent of maximum continuous power instead of at the 84-percent power level, the program goal would most likely have been exceeded. Another factor that seems to be of import is the manner in which the oil is lost. If the oil is lost gradually, allowing the transmission to heat up uniformly, the chances for extended loss-of-lube run time are much better than if the oil system suddenly and completely ceases operation. This is one of the obvious benefits of an emergency lubrication system. It allows the transmission system to heat up gradually and uniformly.

9. SUMMARY OF TESTS PERFORMED

Table 9 is a brief summary of the testing performed under this contract. Although the program goal was not achieved, the historical 5- to 7-minute loss-of-lube capability of the transmission was significantly extended. Furthermore, it appears that a 15-minute loss-of-lube capability for the AH-1S transmission can be achieved with a minimum number of modifications. The modifications to the standard AH-1S transmission to achieve the 15-minute capability would be the following:

- Shim the main input spiral bevel gear set to a minimum of .012-inch backlash.
- Modify the main input triplex bearing with increased internal clearance by increasing the outer race curvature.
- Install a silver-plated steel retainer in place of the bronze retainer in the main input pinion roller bearing.
- Install silver-plated steel retainers in place of the nylatron retainers in the main gearshaft duplex bearing.
- Install silver-plated steel retainer in place of the bronze retainer in the gearshaft roller bearing.
- Install silver-plated steel retainers in place of the bronze retainers of the lower planetary roller bearings and in place of the nylon retainers of the upper planetary roller bearings.
- Install silver-plated steel retainers in place of the bakelite retainers of the planetary ball bearings.
- Install planetary roller guides made of M-50 steel instead of AISI 52100 steel.
- Increase the backlash of the lower planetary sun-planet mesh by modifying the lower sun gear.

The 15-minute capability would be based on a power level of 84 percent of MCP. At lower power levels the loss-of-lube capability would be increased. A temperature probe on the lower ring gear would be an excellent indicator to the pilot of the operating condition of the transmission under loss-of-lube conditions. Once the lower ring gear temperature exceeded 600°F, an immediate landing would be necessitated.

TABLE 9. SUMMARY OF LOSS-OF-LUBE TESTS

Test	Modifications	Loss-of-lube run time (min)	Failure Mode
Xmsn No. 1	Main xmsn bearings modified (Ref. Table 1) Carbon radial input seal installed	7	Main input bevel pinion teeth
Retest of Xmsn No. 1	Main xmsn bearings modified (Ref. Table 1) Carbon radial input seal Main input bevel gear set shimmed to .012-inch backlash	21	Lower planetary stage
Xmsn No. 2	Main xmsn bearings modified (Ref. Table 1) Carbon radial input seal installed Main input bevel gear set shimmed to .012-inch backlash. Upper and lower planet pinions ground to provide increased backlash	19	Lower planetary stage
Fourth Test	Main xmsn bearings modified (Ref. Table 1). Carbon radial input seal installed. Main input bevel gear set shimmed to .012-inch backlash. New lower planet pinions with increased backlash used. Nitrided lower sun gear used. M-50 stl lower planetary bearing inner races used and bearing clearance increase .0005 inch. Oil collectors installed below lower planetary stage.	26.5	Lower planetary stage

10. CONCLUSIONS

The AH-1S HST test program led to the following conclusions:

1. The internal component improvements for the AH-1S transmission system tested under this program extended the loss-of-lube capability of this transmission from about 7 minutes to about 25 minutes, but the 30-minute goal was not achieved. The lower planetary stage appears to be the only area of the modified AH-1S transmission which is not capable of at least 30 minutes of loss-of-lube operation. The single, most beneficial planetary modification tested during this program was probably the installation of the silver-plated steel retainers. The use of M-50 steel for the planetary rollers, roller guides, and bearing inner races as well as the use of the nitrided lower sun gear enhanced the high-temperature operation of the lower planetary stage. The use of oil collectors below the lower planetary had no noticeable, beneficial effect because this oil was lost so quickly. It appeared that increasing the lower planetary gear mesh clearances resulted in no increase in loss-of-lube run time during the tests conducted on this program. However, since maintaining planetary gear mesh clearances are critical, and since standard AH-1S planetary backlashes are relatively small (.0035 inch to .0065 inch), more testing would have to be performed before a conclusion could be drawn.

2. A minimum of .012-inch backlash in the main input spiral bevel gear set was required to achieve a 30-minute loss-of-lube capability for this gear set.

3. Temperatures recorded during the loss-of-lube testing indicated that modified AH-1S upper and lower mast bearings and modified AH-1S tail rotor drive bearings were not required to achieve 30 minutes of loss-of-lube operation of the AH-1S transmission. The standard AH-1S bearings would be adequate for these locations.

4. The thermal testing of the AH-1S HST indicated that in the event of total loss of the oil cooler, the transmission oil temperature would stabilize below 350°F even when operating at maximum continuous power.

5. The modified input triplex bearing exhibited excellent operating temperature characteristics during this program just as it did during the prior AH-1G HST program (reference USAAMRDL-TR-76-8). The inner race temperatures were cooler than the outer race temperatures during lubricated

operation and during nonlubricated operation bearing clearance was always maintained. During the AH-1G HST program the modified triplex bearing was lubricated through both inner and outer races, whereas during this program the modified triplex was only lubricated through the outer race (standard AH-1S lubrication). After the AH-1G HST testing under the previous DAAJ02-74-C-0019 contract, it could not be determined whether the outer race curvature change to the triplex bearing or the lubrication through the inner races was responsible for the improved operating characteristics of this bearing. Now it may be concluded that the outer race curvature change was responsible for the improved performance of the triplex bearing.

6. The carbon radial seal used in the main input quill of the test transmissions demonstrated excellent sealing capabilities at elevated operating temperatures. The physical installation of this seal is somewhat more difficult than the standard AH-1S elastomeric lip seal. The wear sleeve for the carbon seal must be pinned to the freewheeling unit outer race to prevent the wear sleeve from turning. Based on the work done under this program, no conclusion can be reached as to which seal is superior during normal transmission operation.

11. RECOMMENDATONS

1. As a minimum program designed to significantly improve the loss-of-lube survivability of the AH-1S helicopter, the internal component improvements listed in Section 9 of this report should be incorporated on the AH-1S transmission.

2. A 30-minute lube-loss capability for the AH-1S transmission can be achieved if the loss-of-lube performance of the lower planetary stage can be further improved. A program to accomplish this should be conducted and should consider the suggestions offered in Section 8.4 of this report.

3. The thermal tests conducted under this program indicate that elimination of the transmission oil cooler would be feasible if the transmission cases, gears, bearings and other components as well as the lubricant itself could operate continuously at temperatures approaching 400°F. Programs to effect these capabilities should be undertaken.